Theories and observations of disc evolution - is a paradigm shift happening?

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Science and Technology Facilities Council

Demographics of young stars and their protoplanetary disks: lessons learned on disk evolution and its connection to planet formation

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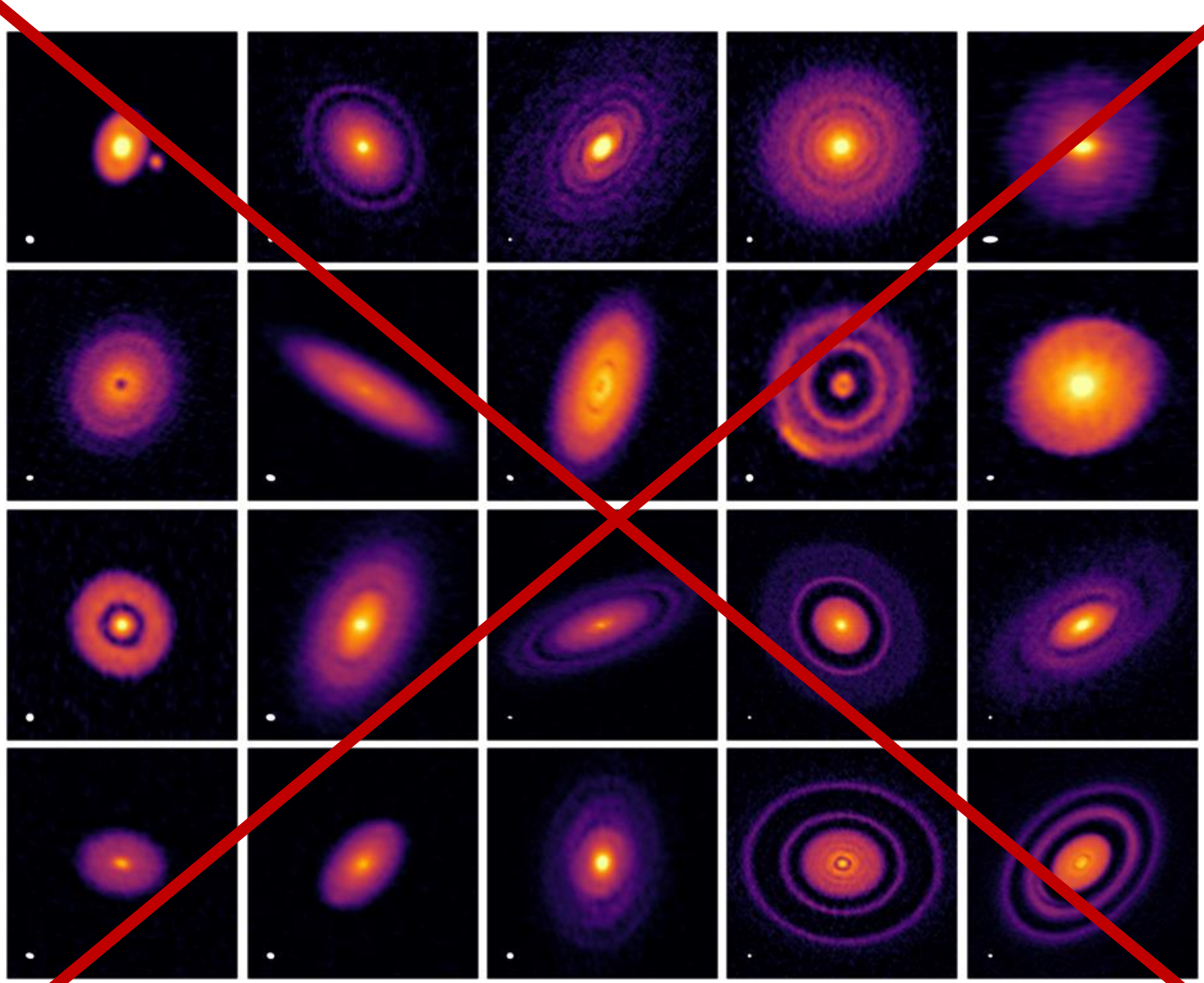

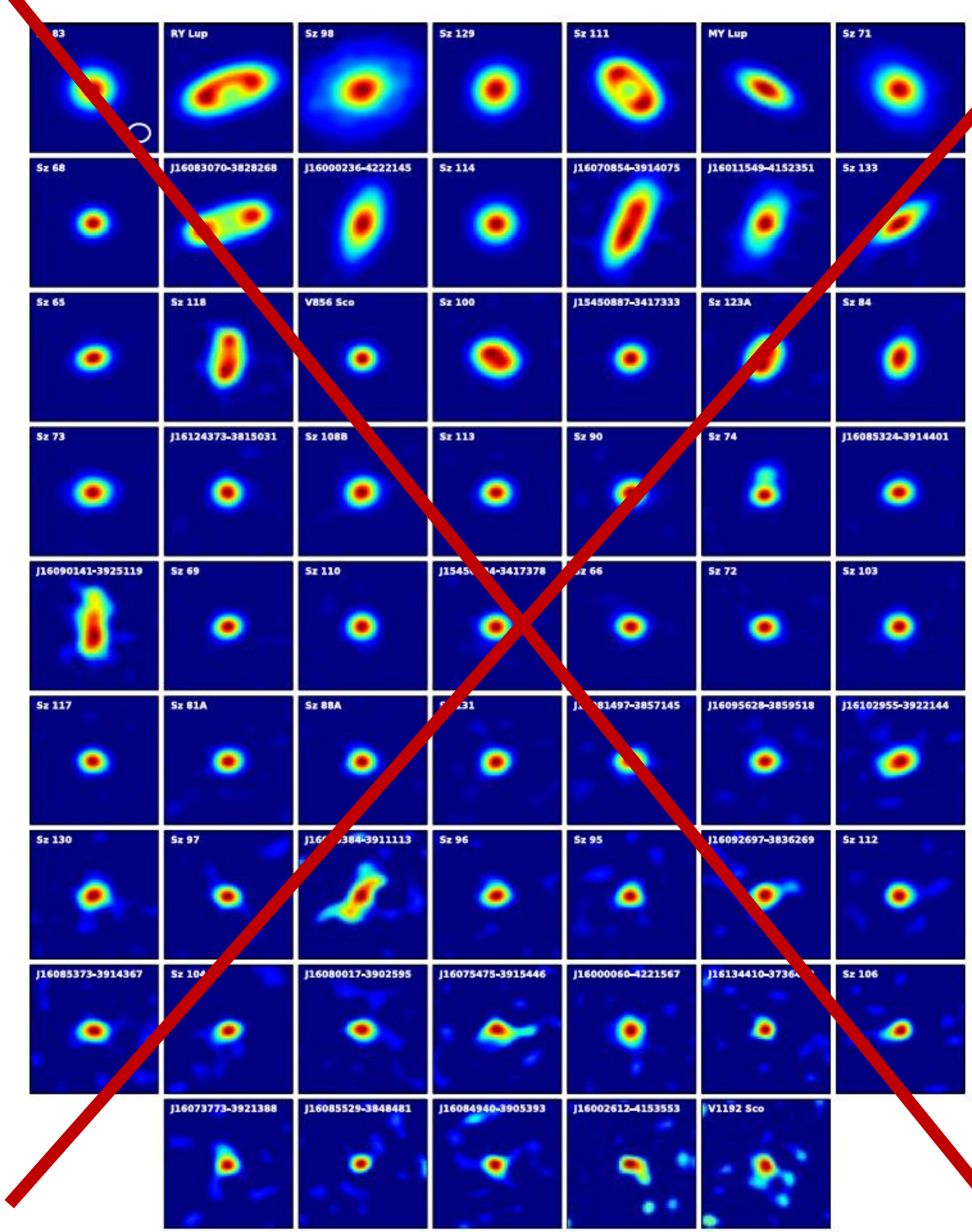
83
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Sz 129
Sz 111
MY Lup
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Sz 118
V856 Sco
Sz 100
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Sz 90
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Sz 72
Sz 103
Sz 117
Sz 81A
Sz 88A
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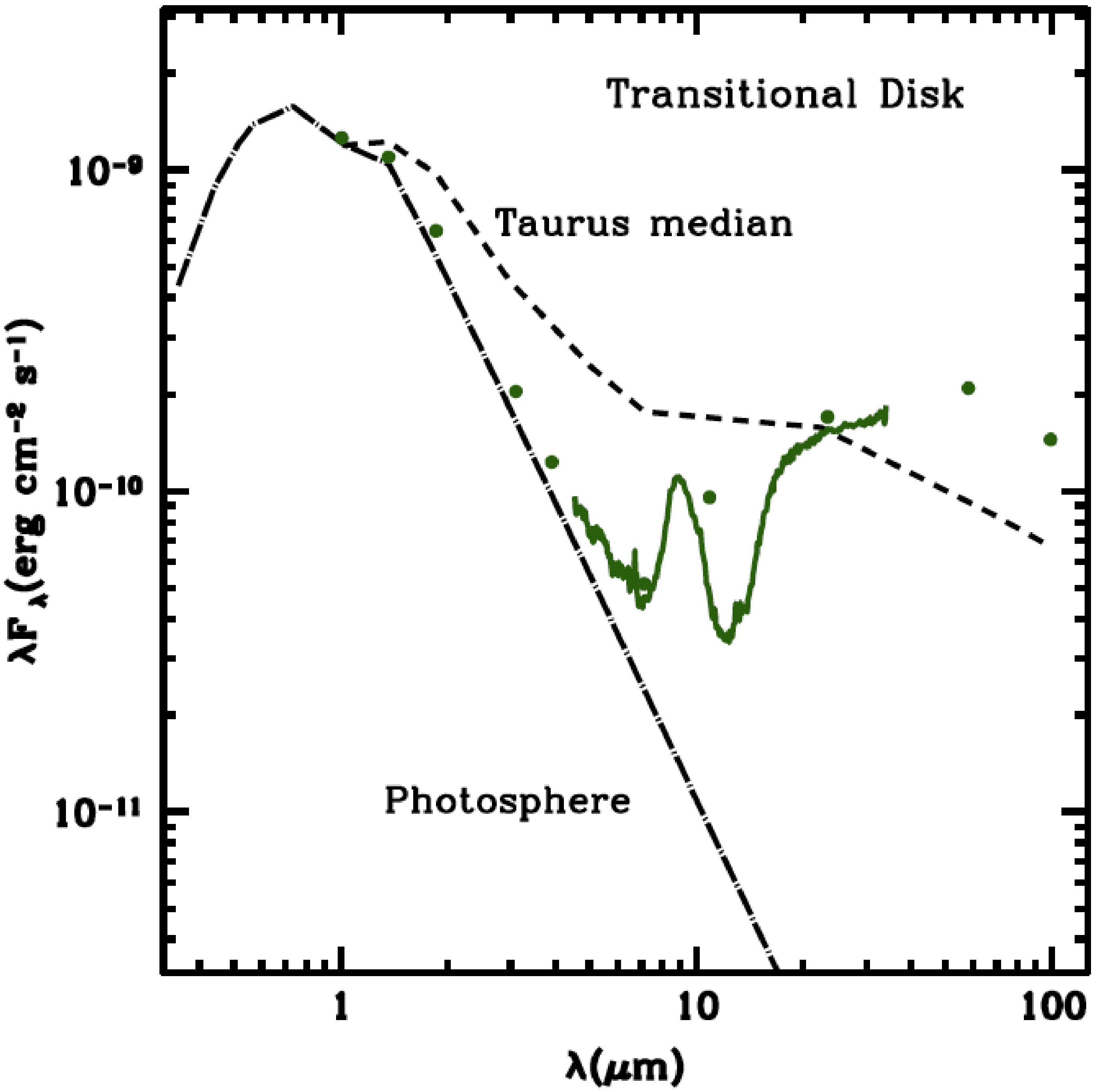
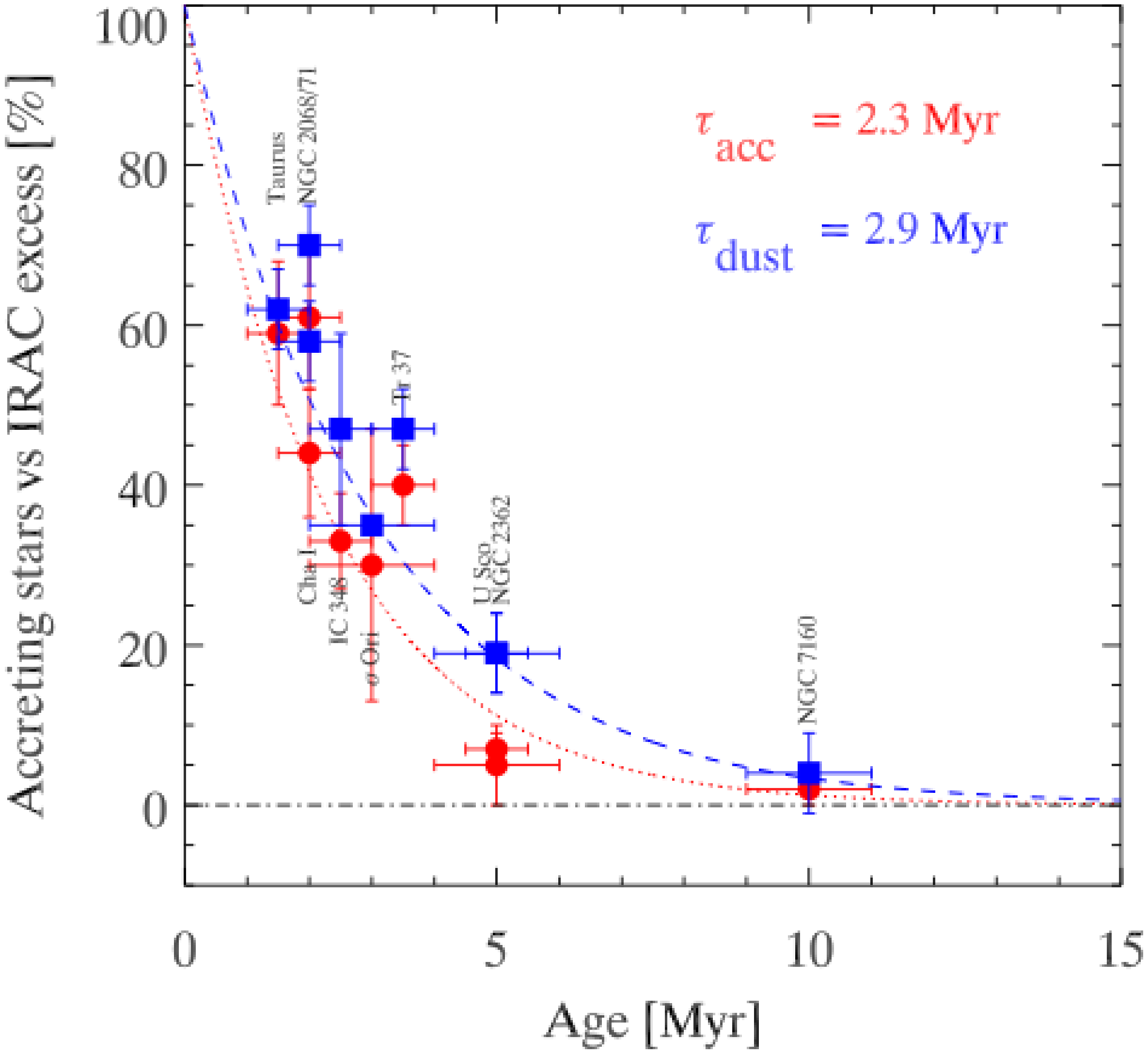

Transitional Disk
Taurus median
Photosphere
λF_λ(erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
1
10
100
λ(μm)

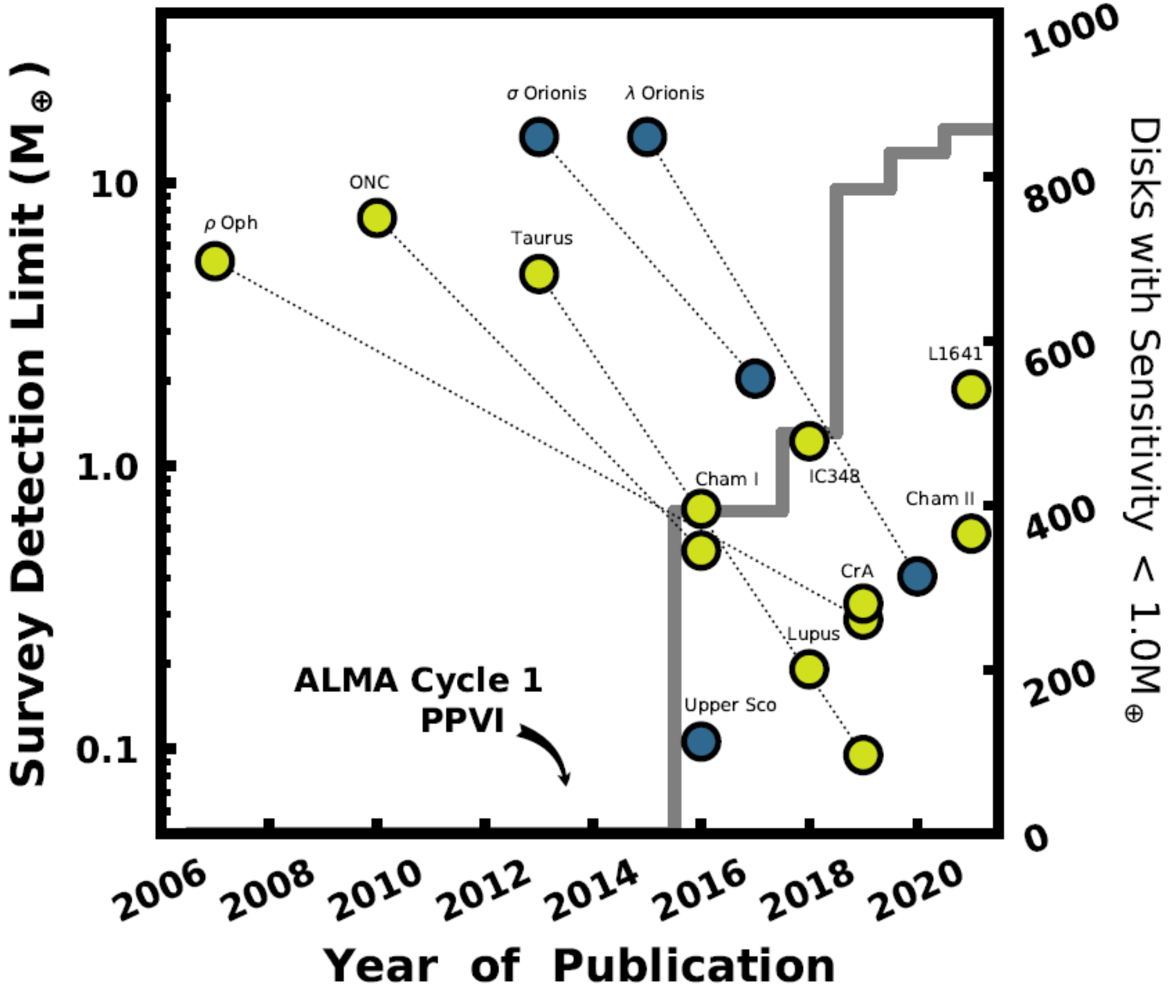
Observational constraints

Median disc lifetime: a few Myr

Fedele+ 2010

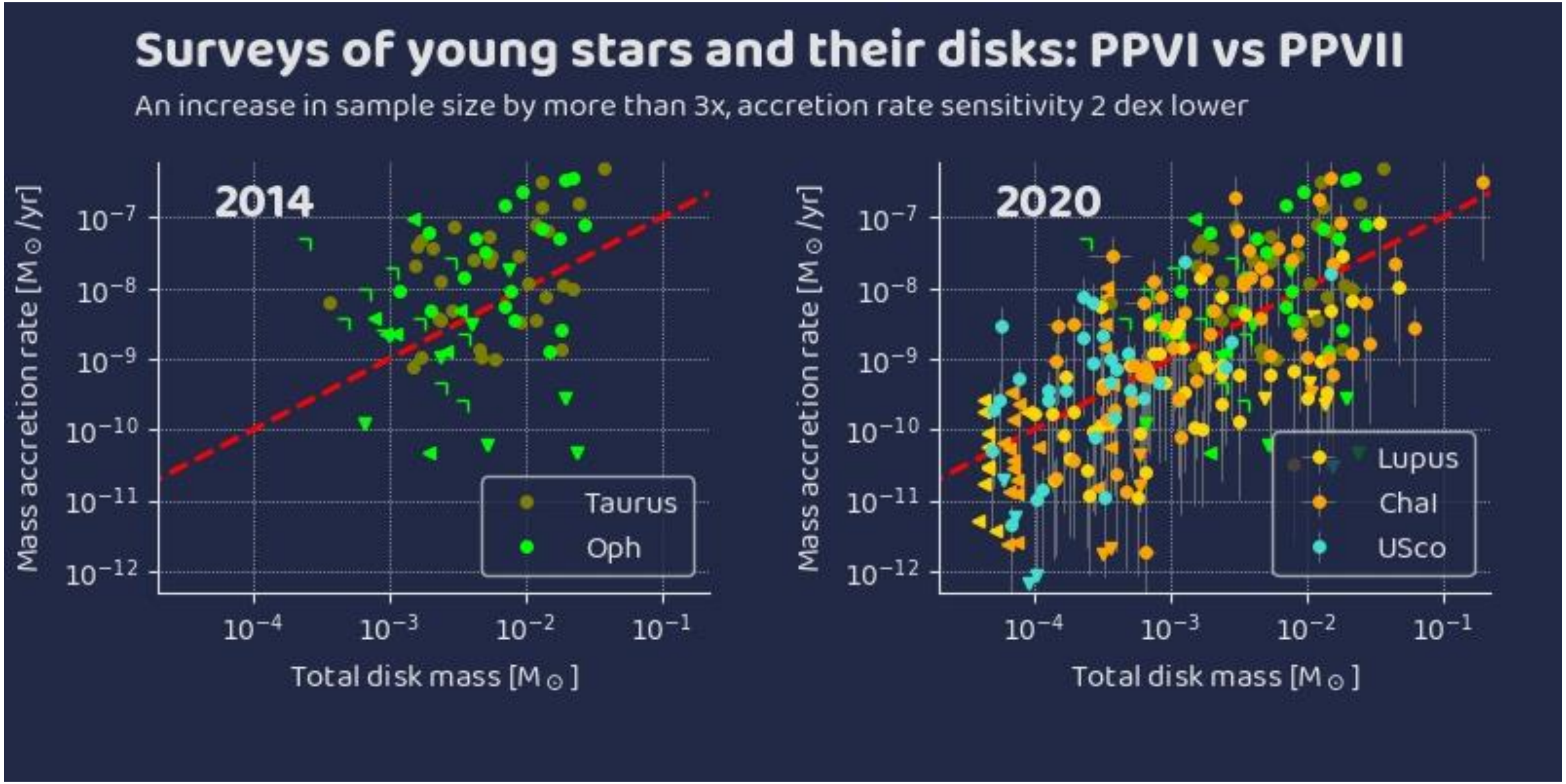


How the landscape has changed



Almost reached the 1000 count

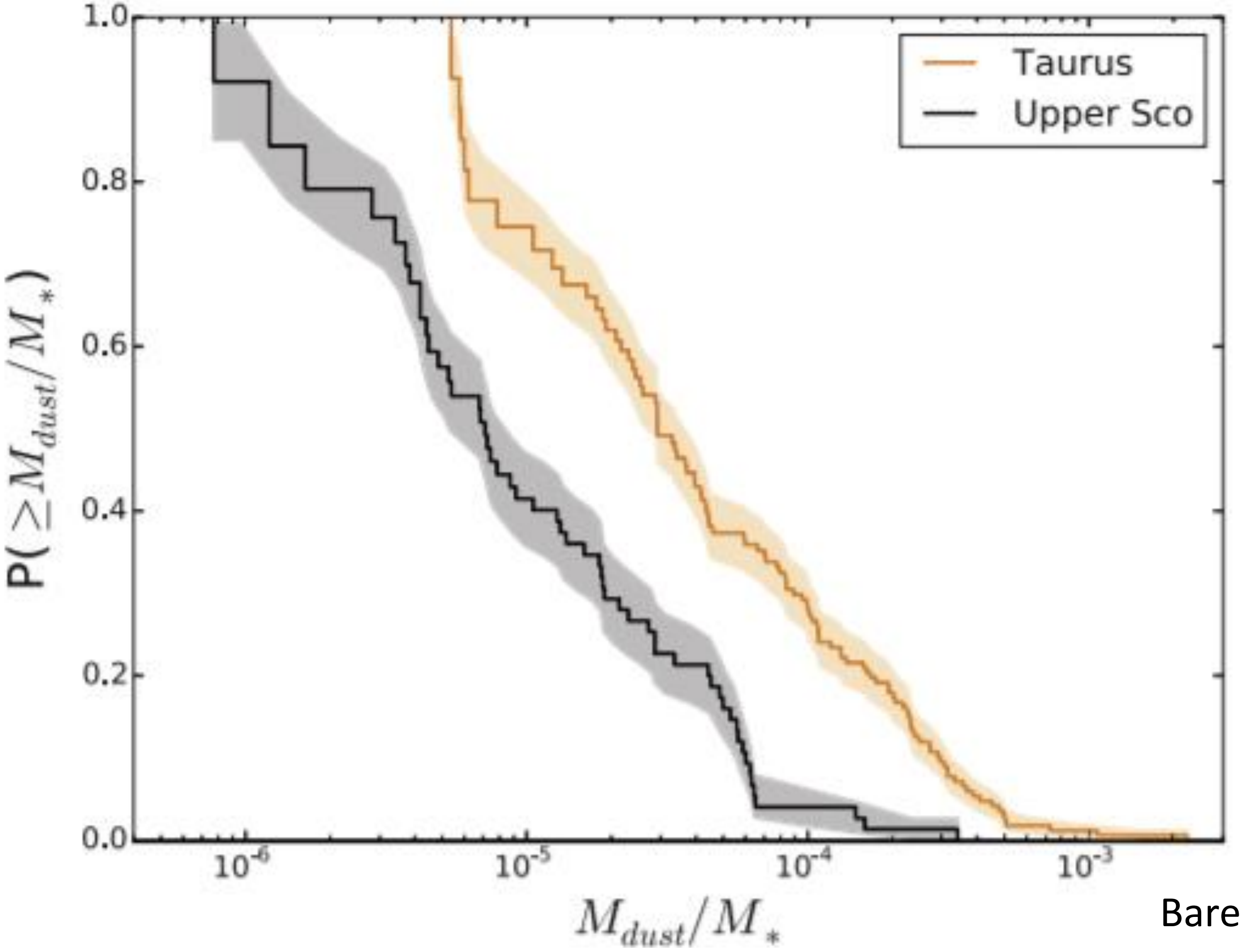
Combining with accretion rates



Surveys of young stars and their disks: PPVI vs PPVII

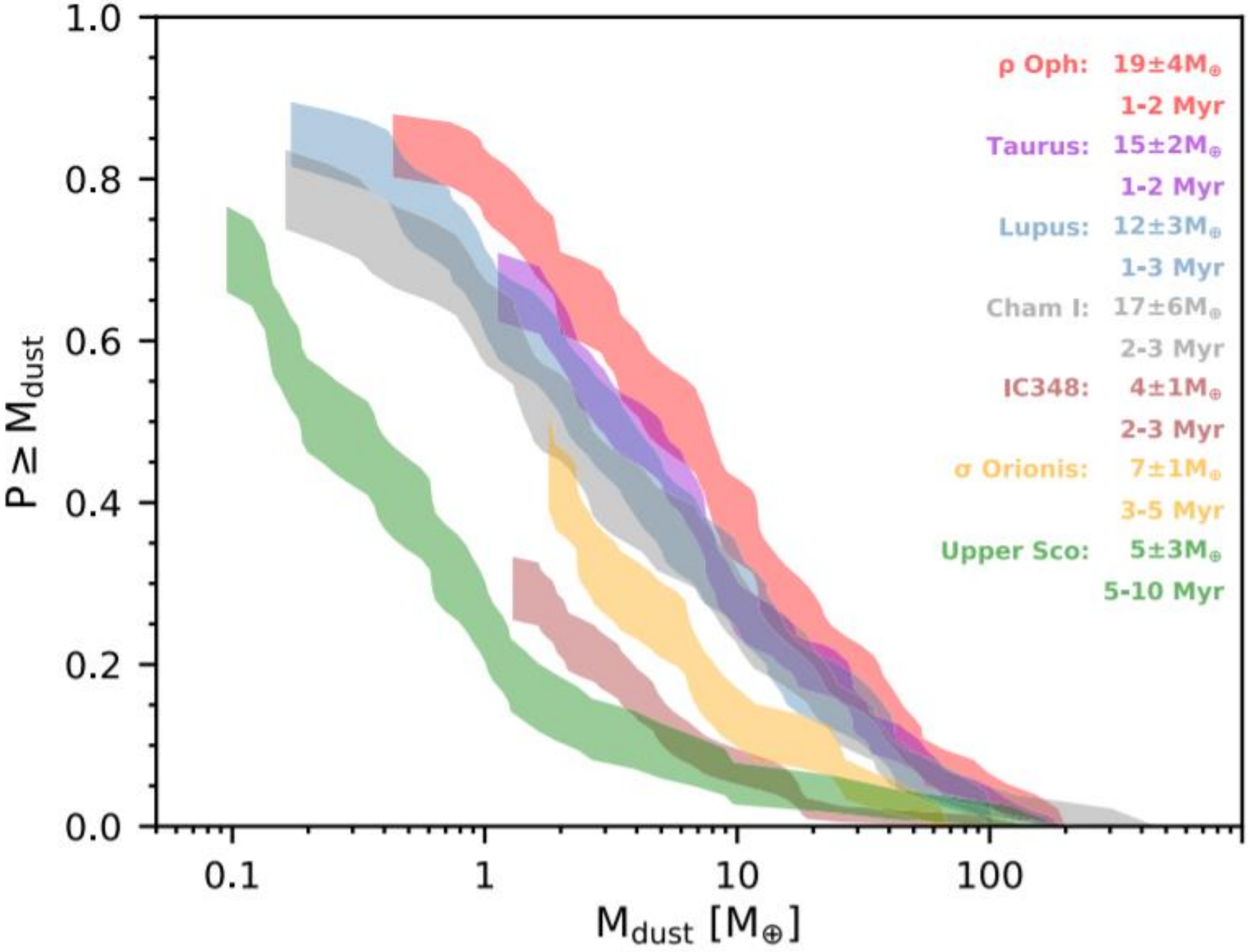
An increase in sample size by more than 3x, accretion rate sensitivity 2 dex lower

Number of regions keeps increasing



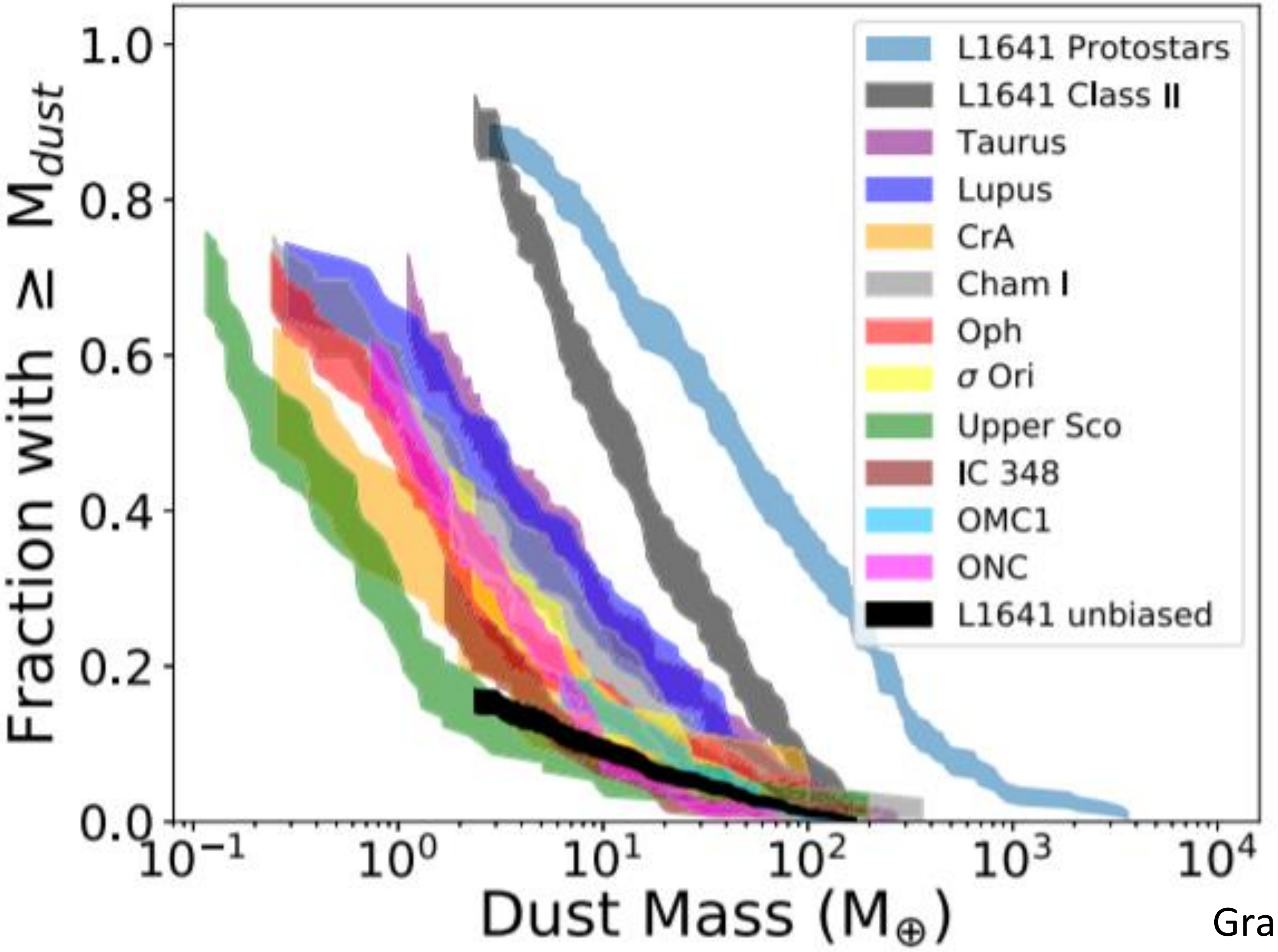
Barenfeld+ 2016

Number of regions keeps increasing



Cieza+ 2019

Number of regions keeps increasing



Grant+ 2021

Sample compiled for the review

Region name	Number of sources	Age (Myr)	Reference for sub-mm	Reference for accretion rate
Ophiucus	279	1-2	Cieza et al. 2019	Testi et al, submitted
Taurus	210	1-2	Andrews et al. 2013	Herczeg & Hillenbrand 2014, Ingleby et al 2013, Manara et al 2014, Alcala et al 2021, …
Lupus	95	1-3	Ansdell et al. 2016, 2018	Alcala et al 2014
Chameleon I	93	2-3	Pascucci et al. 2016	Manara et al 2016, 2017
Chameleon II	29	~4 (?)	Villenave et al 2021	Villenave et al 2021
Corona Australis	122	1-3	Cazzoletti et al. 2019	Testi et al, submitted
Upper Sco	106	5-10	Barenfeld et al. 2016	Manara et al 2020

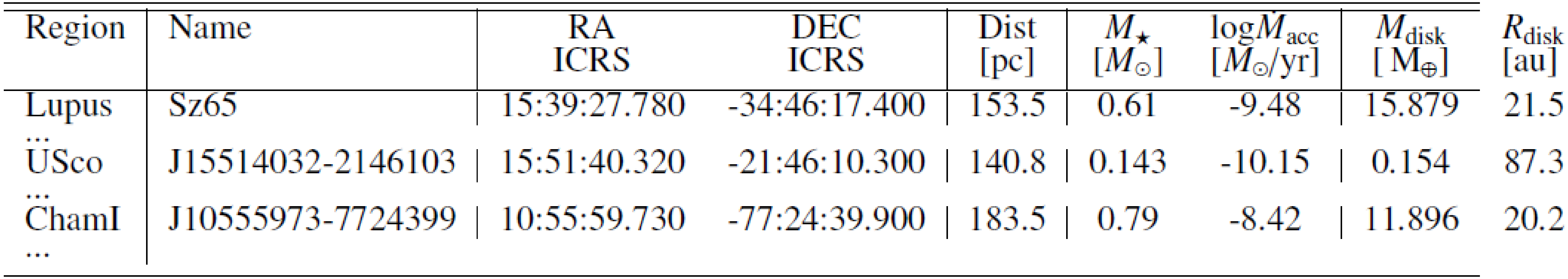
We restricted the compilation to regions within 300pc.
Dust mass sensitivity: < 1 Earth mass. Stars down to late-M SpT

Caveats

- Taurus is still patchy and incomplete
  - Most of the sub-mm data (Andrews et al 2013) is pre ALMA
  - Stellar properties: Herczeg & Hillenbrand 2014, but no accretion rates

- Completeness 80-90%. Disc sample based on Spitzer, but Gaia (e.g. Manara et al 2018, Beccari et al 2018, Luhman et al 2020a,b, …) reveals more members spread out over larger regions.

Data provided



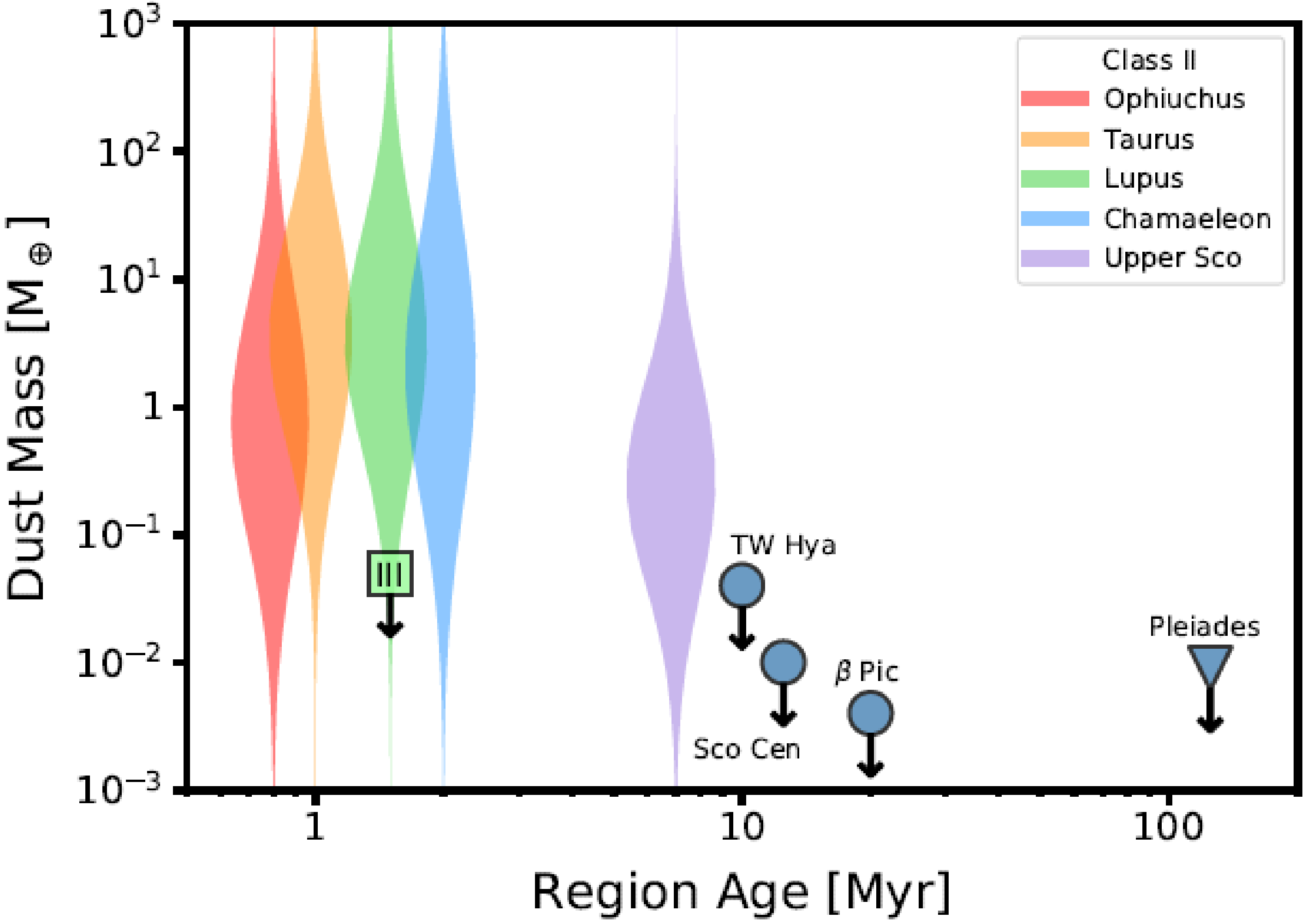
Region	Name	RA ICRS	DEC ICRS	Dist [pc]	$M_\star$ $[M_\odot]$	$\log \dot{M}_{\rm acc}$ $[M_\odot/{\rm yr}]$	$M_{\rm disk}$ $[{\rm M}_\oplus]$	$R_{\rm disk}$ [au]
Lupus	Sz65	15:39:27.780	-34:46:17.400	153.5	0.61	-9.48	15.879	21.5
...								
USco	J15514032-2146103	15:51:40.320	-21:46:10.300	140.8	0.143	-10.15	0.154	87.3
...								
ChamI	J10555973-7724399	10:55:59.730	-77:24:39.900	183.5	0.79	-8.42	11.896	20.2
...								

- Disc mass: $$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$
- Radius from Hendler et al (2020), if available

Gas properties

- We do not provide *gas* (CO) measurements because of low detection rate and issues with unknown abundance (e.g. Bergin+ 2013, Miotello+ 2017, …)
- Gas is faint even for ALMA!
- Stay tuned for new ALMA LP AGE-PRO (PI: Coco Zhang)

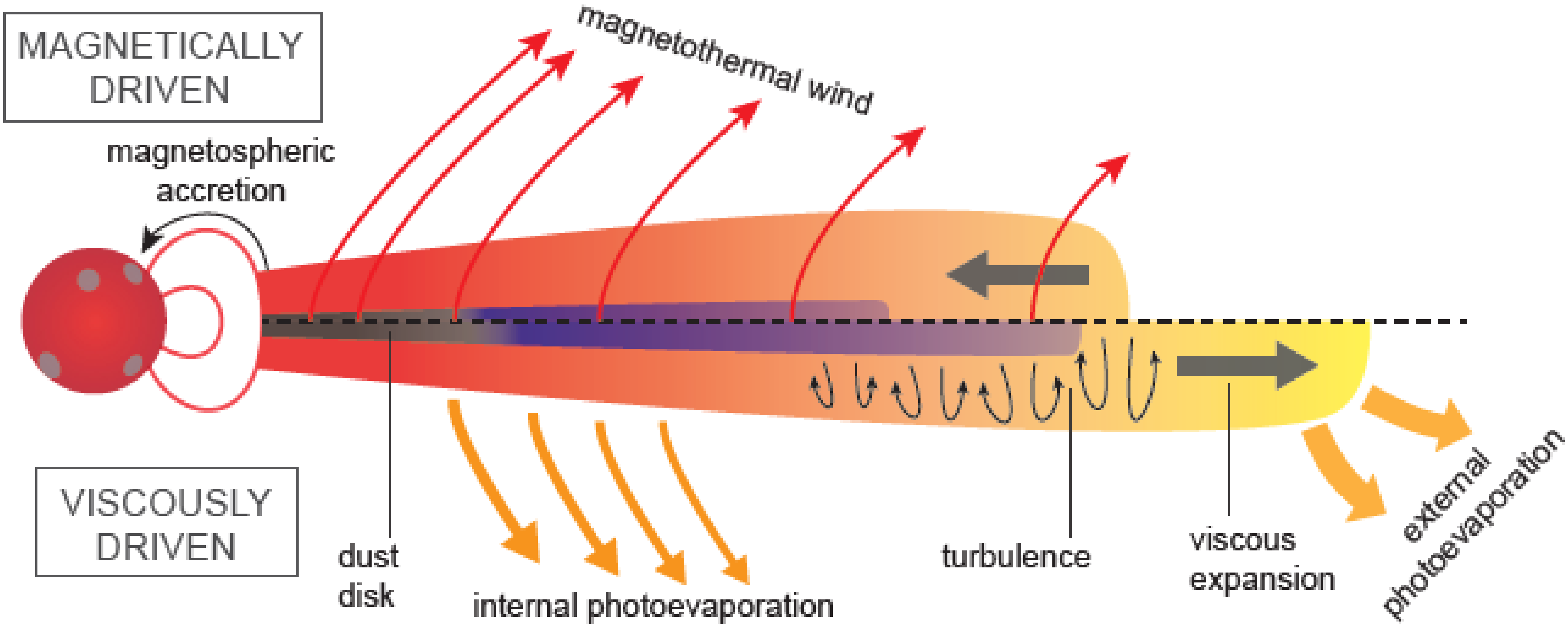
Evolution of the dust mass



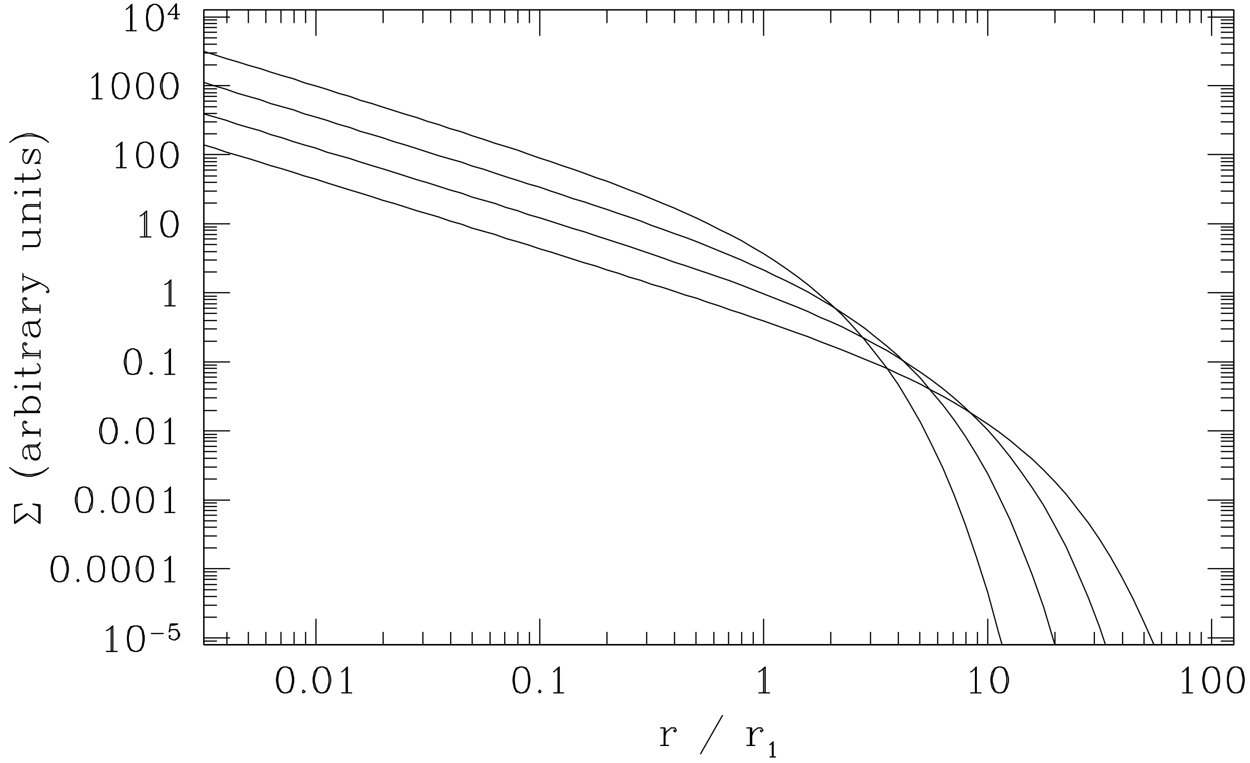
General decrease with age, though Ophiucus and CrA out of the trend

Different initial conditions? Complicated star formation history?

The big debate



Most long-term models are run in viscous framework



$$\Sigma(\tilde{r},T) = \frac{C}{3\pi\nu_1\tilde{r}^{\gamma}} T^{-(5/2-\gamma)/(2-\gamma)} \exp\left[-\frac{\tilde{r}^{(2-\gamma)}}{T}\right]$$

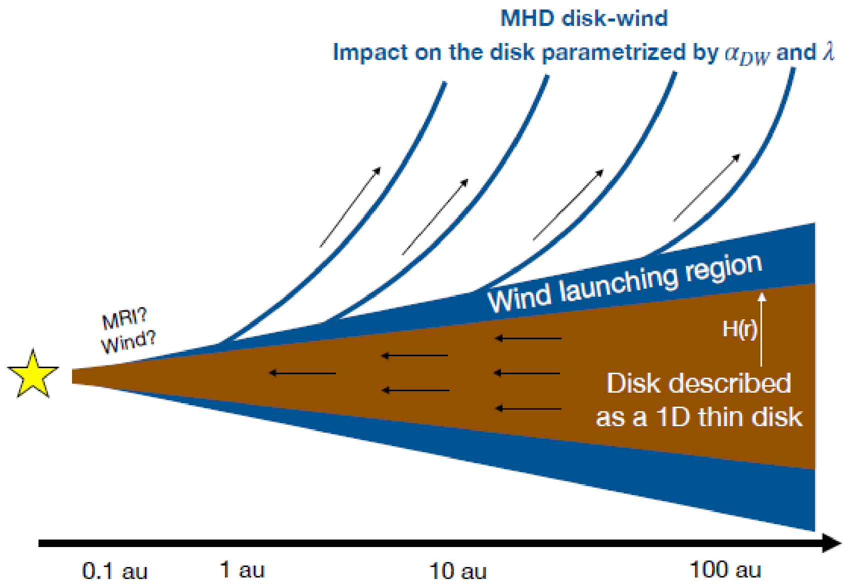
Lynden-Bell & Pringle (1974)

Why? Probably because it is *simple*

“Given the limited nature of the observational data available, we wish to apply simple models with a minimum of parameters” (Hartmann+ 1998)

Can we build a simple model including winds?

New prescription equivalent to Shakura-Sunyaev. Different approach from including more physically motivated models (Suzuki 2010, Armitage 2013, Bai 2016, …)



$$\partial_t \Sigma = \frac{3}{r}\partial_r\left[\frac{1}{r\Omega}\partial_r(r^2\alpha_{SS}\Sigma c_s^2) + \frac{\alpha_{DW}\Sigma c_s^2}{2\Omega}\right] - \frac{3\alpha_{DW}\Sigma c_s^2}{4(\lambda-1)r^2\Omega}$$

Vertical transport of AM by turbulence

$$\alpha_{SS} = \frac{1}{\Sigma c_s^2}\bar{B}_r\bar{B}_\phi$$

Vertical transport of AM by MHD disk-wind

$$\alpha_{DW} = \frac{4r}{3\Sigma c_s^2}\left(B_z B_\phi\right)_{-h_w}^{h_w}$$

'torque due to the wind'

Mass loss-rate due to the wind

$$\lambda = \frac{j_{wind}}{j_{Disk}}$$

'efficiency of the wind to extract AM'

$$\frac{\textbf{Accretion due to the wind}}{\textbf{Accretion due to turbulence}} \sim \frac{\alpha_{DW}}{\alpha_{SS}} \equiv \psi$$

Tabone, GR+, submitted

Steady-state solution

Assumption: α_{SS}, α_{DW}, and λ are constant in space!
$+ \, T(r) \propto r^{-1/4}$

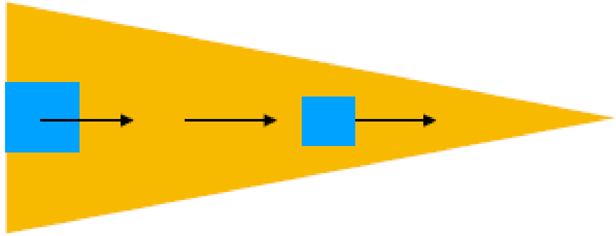
=> constant advection velocity due to the wind and turbulence

degeneracy with $\alpha \propto r^{1-\gamma}$!

$$\mathbf{v}_{acc} = \mathbf{v}_{SS} + \mathbf{v}_{DW} \propto \alpha_{SS} + \alpha_{DW}$$

Viscous case

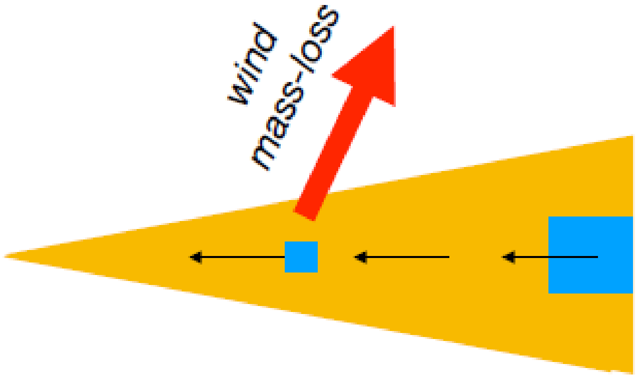
$$\Sigma(r) \propto r^{-1}$$

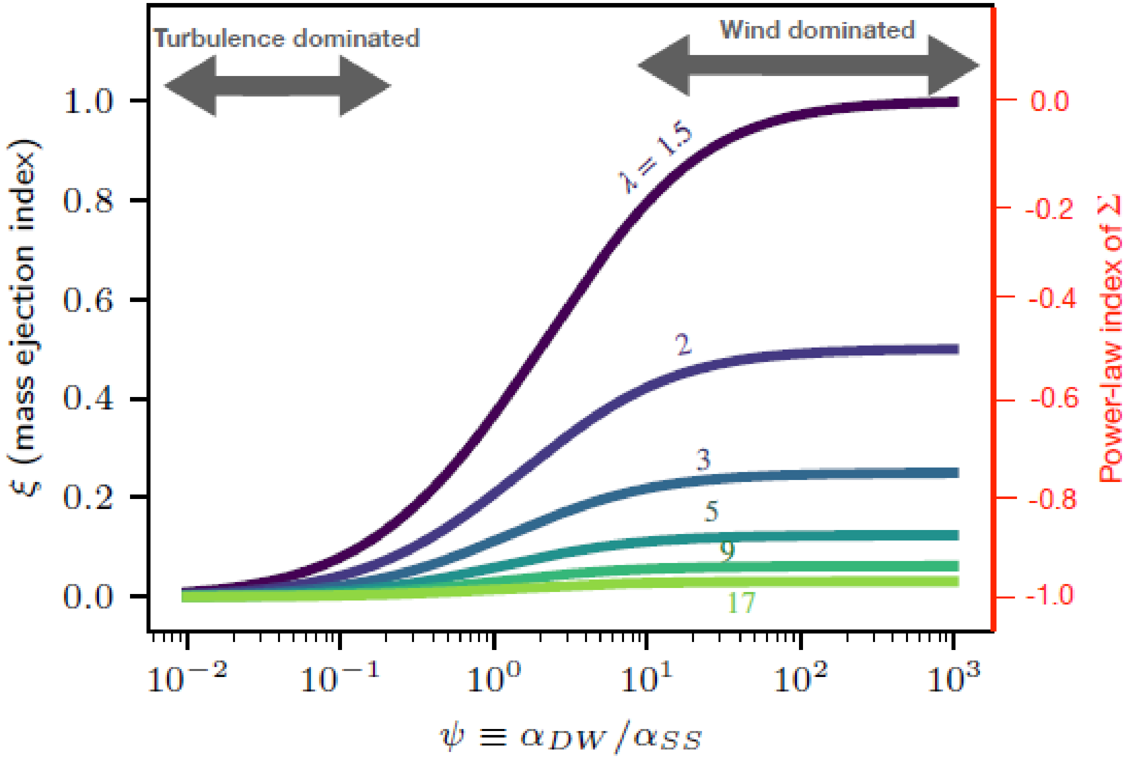


Wind case

flatter profile due to mass-loss!

$$\Sigma(r) \propto r^{-1+\xi}$$





Extension of the Lynden-Bell&Pringle self-similar solution

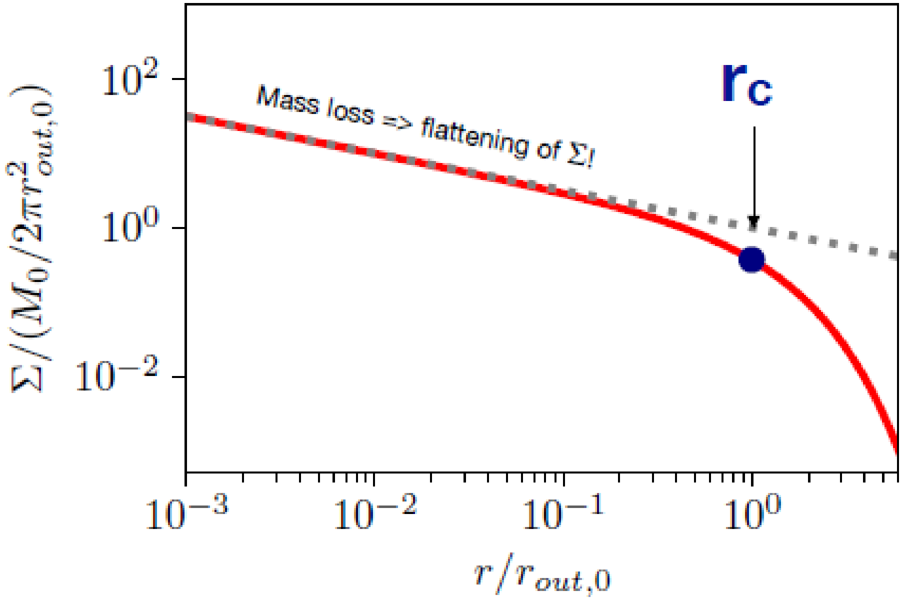
Assumption: α-parameters and λ are constant in space & time

Lynden-Bell & Pringle solution

$$\Sigma(r,t) = \Sigma_c(t)\ \left(r/r_c(t)\right)^{-1}\ e^{-r/r_c(t)}$$

=> timescale: $t_\nu = \dfrac{r_0}{3\epsilon c_{s,0}^2 \alpha_{SS}}$

Ansatz



Generalized solution

$$\Sigma(r,t) = \Sigma_c(t)\ \left(r/r_c(t)\right)^{-1+\xi}\ e^{-r/r_c(t)}$$

=> time required to advect the gas initially at $r_c(t)/2$:

$$t_{\mathrm{acc}} \equiv \frac{r_0}{3\epsilon_0 c_{s,0}^2 \tilde{\alpha}}$$

($\tilde{\alpha} = \alpha_{SS} + \alpha_{DW}$)

Disk radius : estimate of the viscous time scale

Same form as in the pure viscous case!!

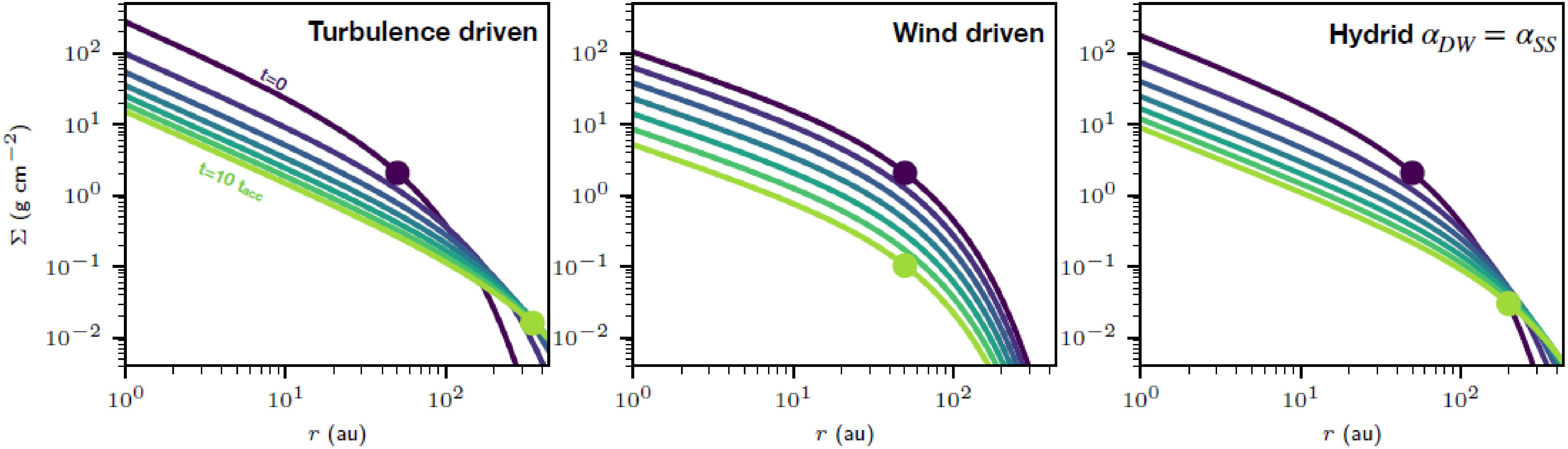
$$r_c(t) = r_c(0)\ (1 + t/t_\nu) \qquad t_\nu \equiv \frac{r_0}{3\alpha_{SS}\epsilon c_s^2}$$

However, for the same accretion time-scale:

$$t_\nu \geq t_{acc}$$

=> viscous speading slower as the contribution of the MHD-DW increases

=> could estimate alpha_SS even in the wind dominated case!

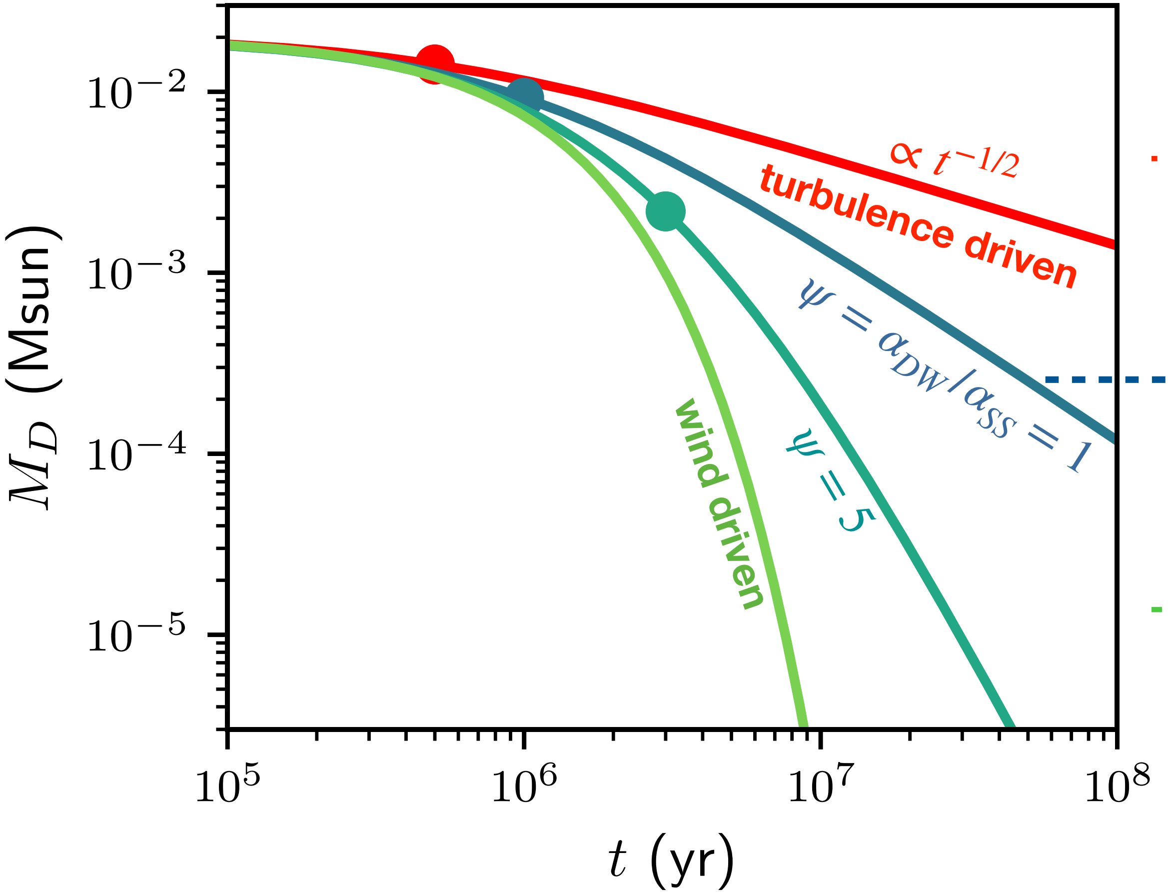


Disk mass: exponential decay in the wind dominated case

Different evolution ultimately due to disk spreading, not mass-loss rate!

In the wind case: decrease gives tacc so α !

Degeneracy: viscous case with $\gamma = 1 + 2\psi$



Viscous spreading
= delay the draining of the disk
= Zeno paradox!!!
$t_{acc}(t) \propto r_c(t) \propto t$

Hybrid:
power-law index ~ $\frac{1}{2}(\psi + 1)$

No viscous speading
=draining of the full disk after
t~2tacc

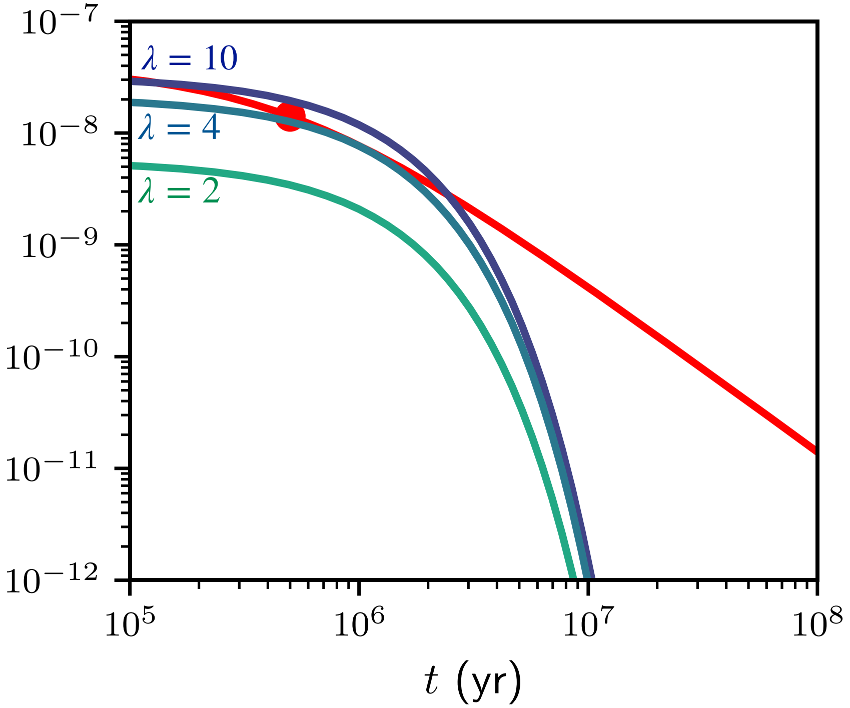
Stellar accretion rate: impact of λ

(1) Stellar accretion rate = time derivative of the disk mass reduced by the fraction of mass ejected in the wind

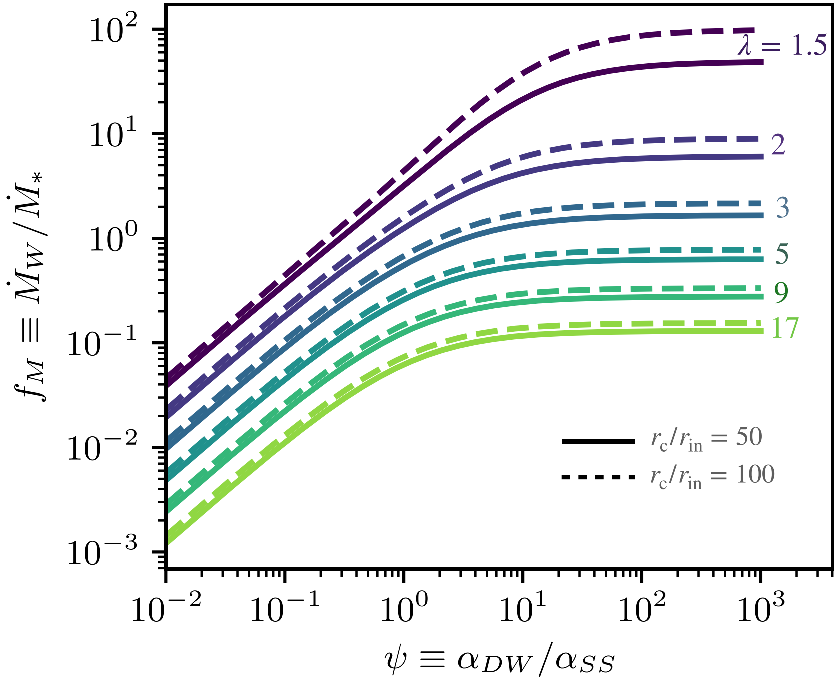
(2) Stellar accretion rate depends on the radial extent r_c/r_{in} , ψ and λ (via f_M)

$$\dot{M}_*(t) = \frac{1}{1 + f_M(t)} \dot{M}_D(t) \qquad f_M(t) \equiv \frac{\dot{M}_W}{\dot{M}_*}$$

Stellar accretion rate



f_M depends on the radial extent r_c/r_{in} , ψ and λ !

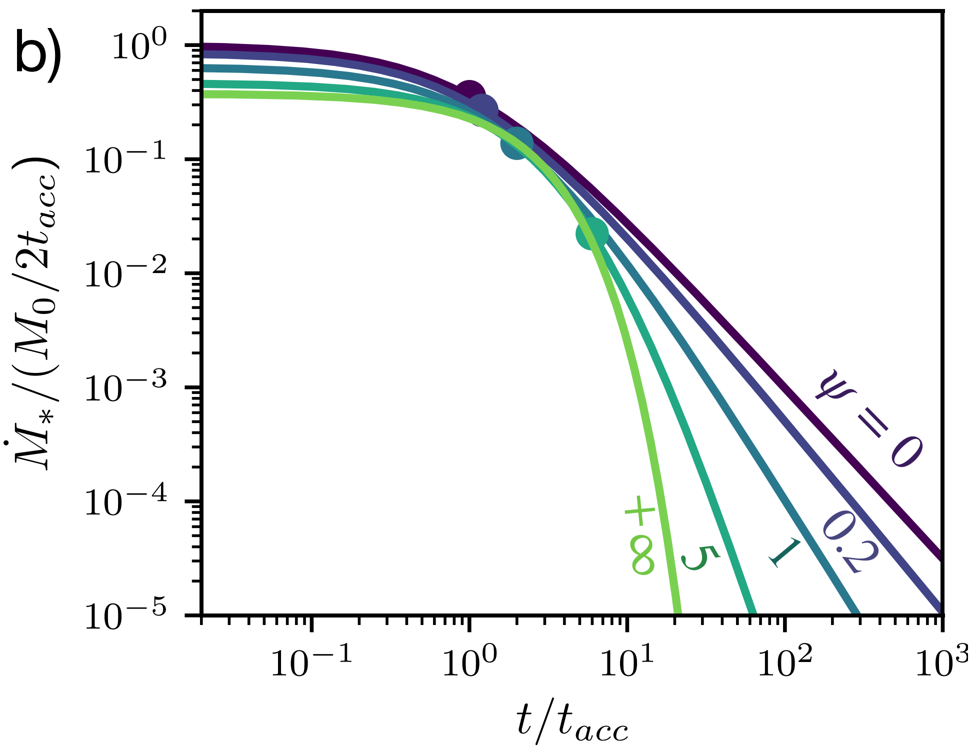


Stellar accretion rate: impact of $\psi = \alpha_{DW}/\alpha_{SS}$

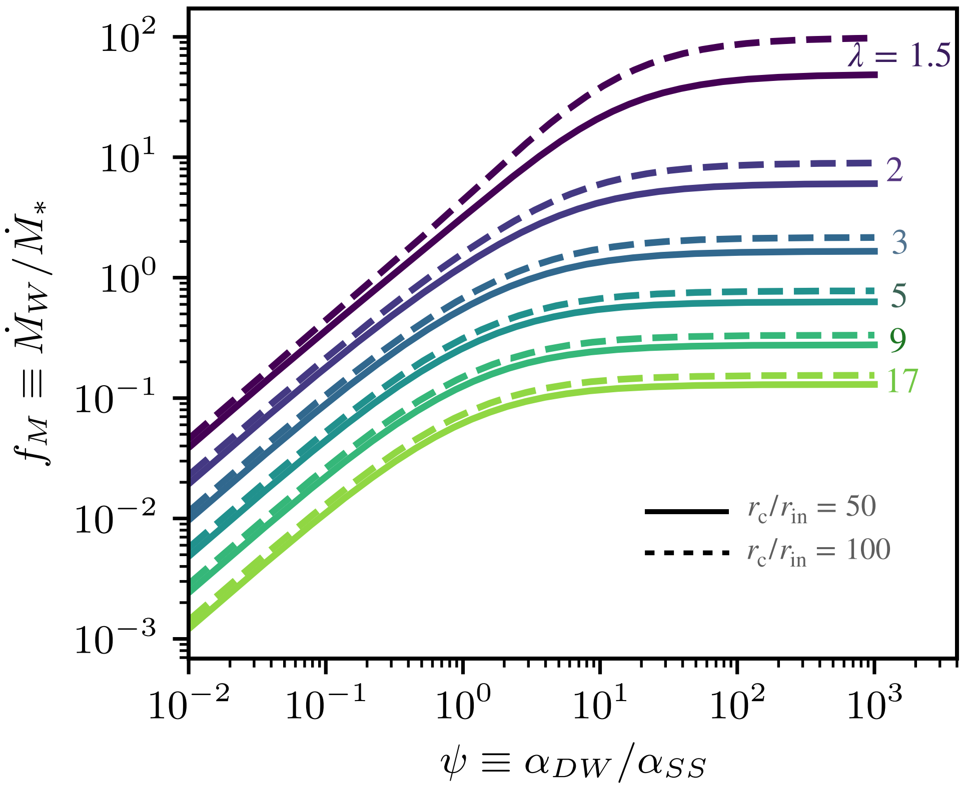
Power-law dependence : still degeneracy btw γ and ψ

Absolute value: mass loss rate depends on ψ

$$\dot{M}_*(t) = \frac{1}{1 + f_M(t)} \dot{M}_D(t) \qquad f_M(t) \equiv \frac{\dot{M}_W}{\dot{M}_*}$$



f_M depends on the radial extent r_c/r_{in} , ψ and λ !



A new class of solution

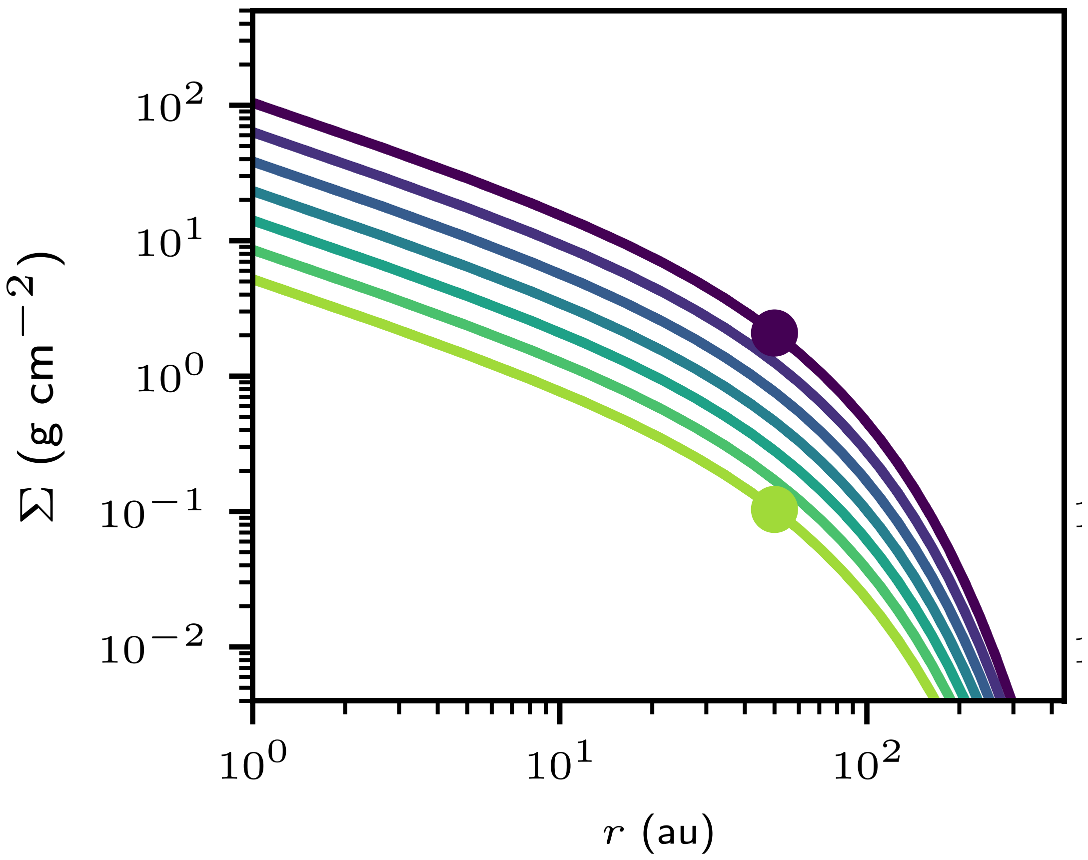
$$\alpha_{DW} = \frac{4r}{3\Sigma c_s^2}\left(B_z B_\phi\right)_{-h_w}^{h_W} \propto \beta^{-1}$$

New class of solution

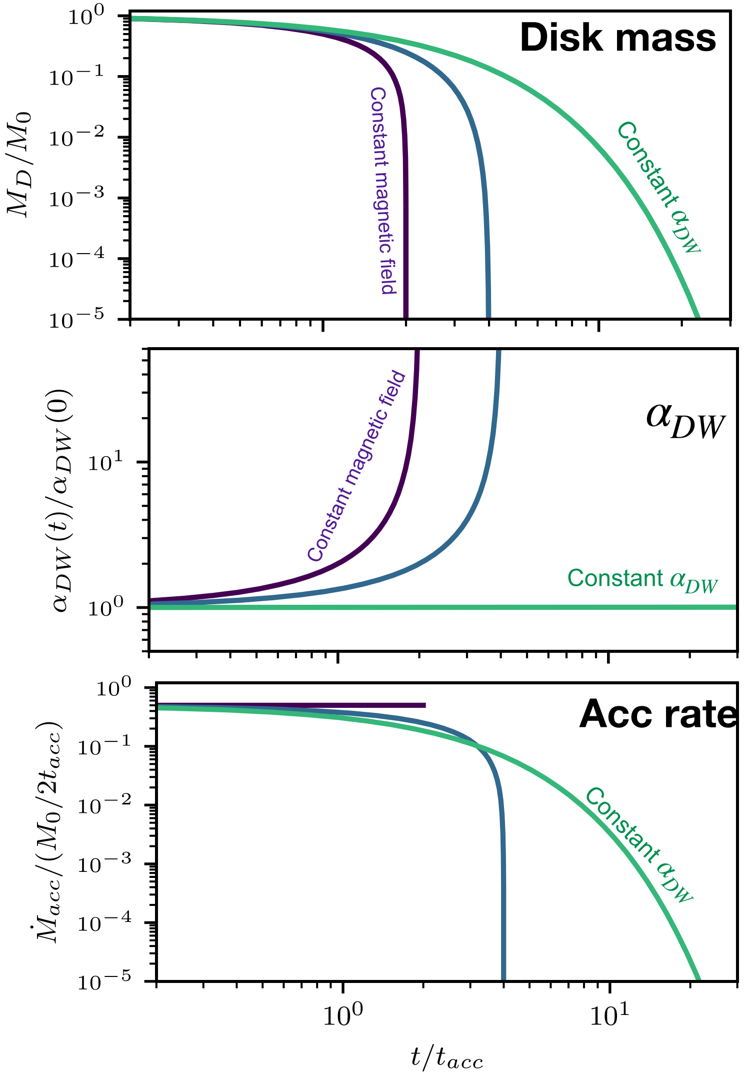
- $\alpha_{SS} = 0$: to get analytical solutions
- $\alpha_{DW} \propto M_D^{-\omega}$ and constant in space

=> ω parametrizes dissipation of the magnetic field

=> constant magnetic field strength $\omega = 1$



A new class of solution



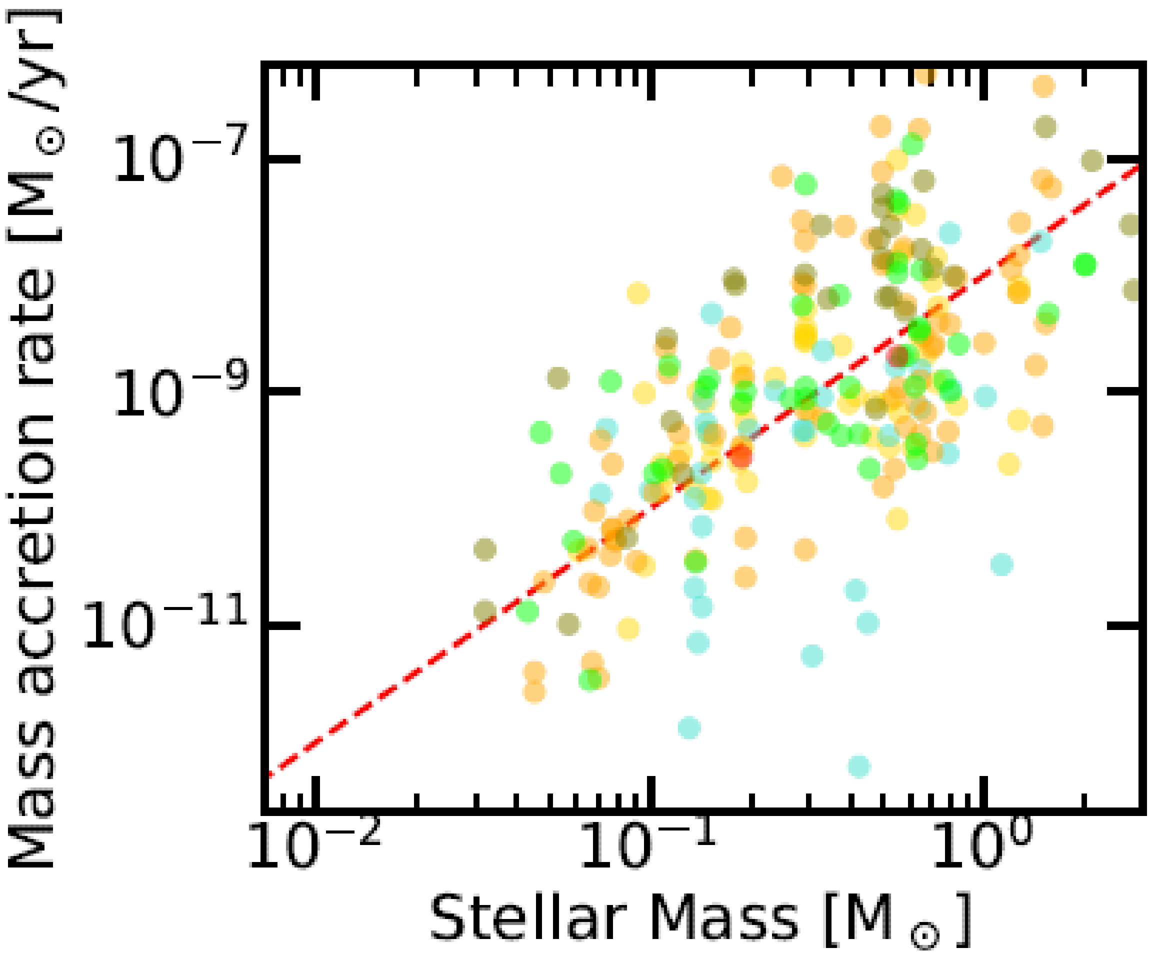
$$\alpha_{SS} = 0 \; ; \alpha_{DW} \propto M_D^{-\omega}$$

Result:

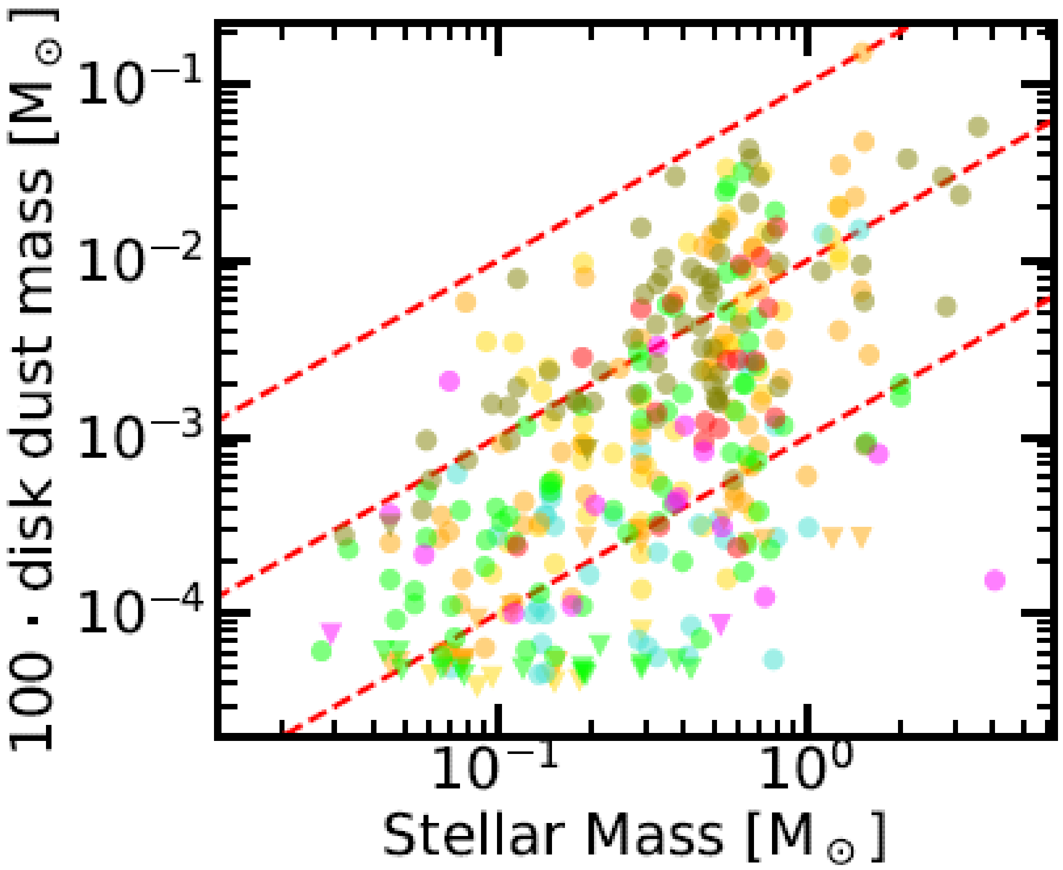
- **Full dispersal of the disk (cf Armitage+2013) at finite time!**
- **Dispersal time: $t_{diss} = t_{acc}/2\omega$ => disk disperal and accretion are driven by the same process!**

Comparison with the data - correlations

Correlations with stellar mass



Hillenbrand+ 1992, Natta+ 2006, …



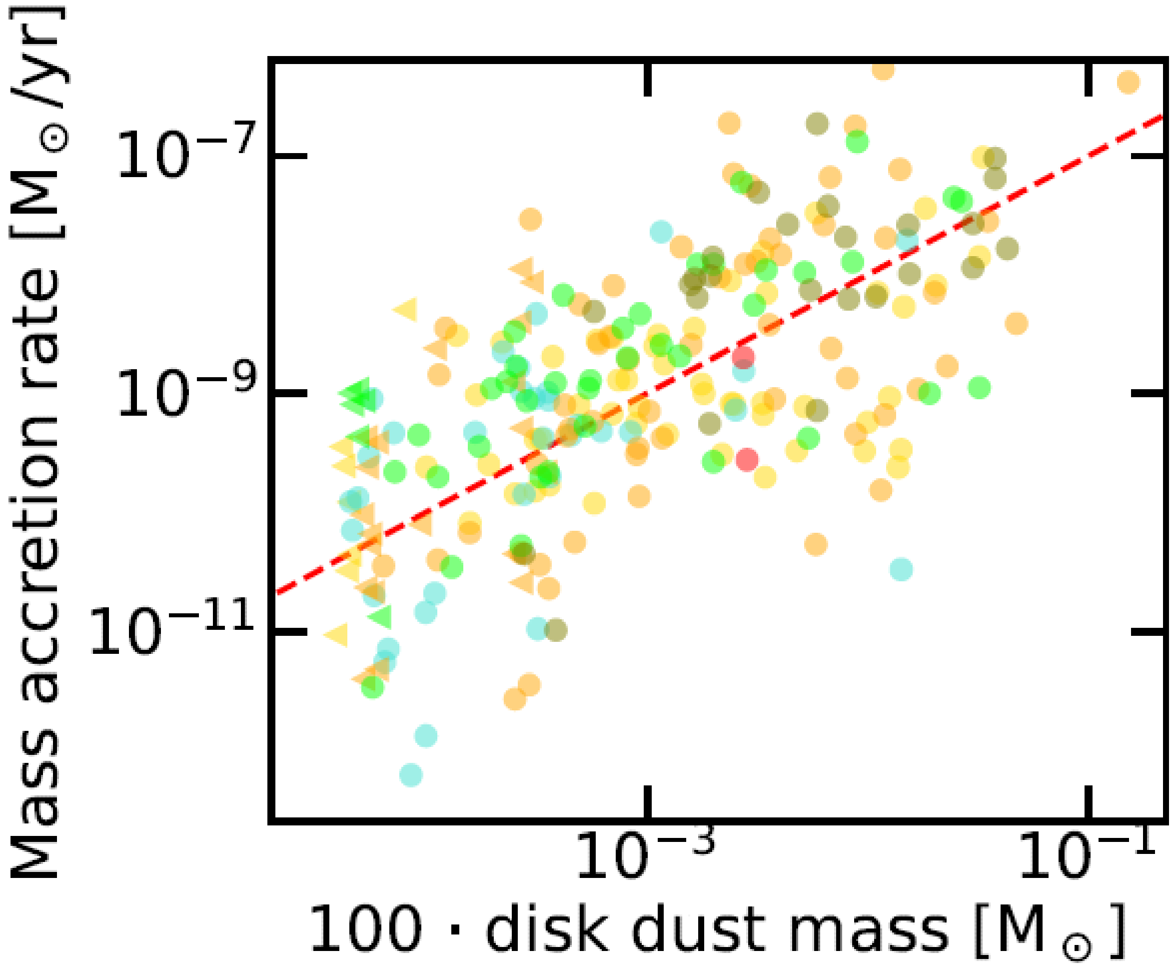
Pascucci+ 2016, Ansdell+ 2017, …

Correlations with stellar mass

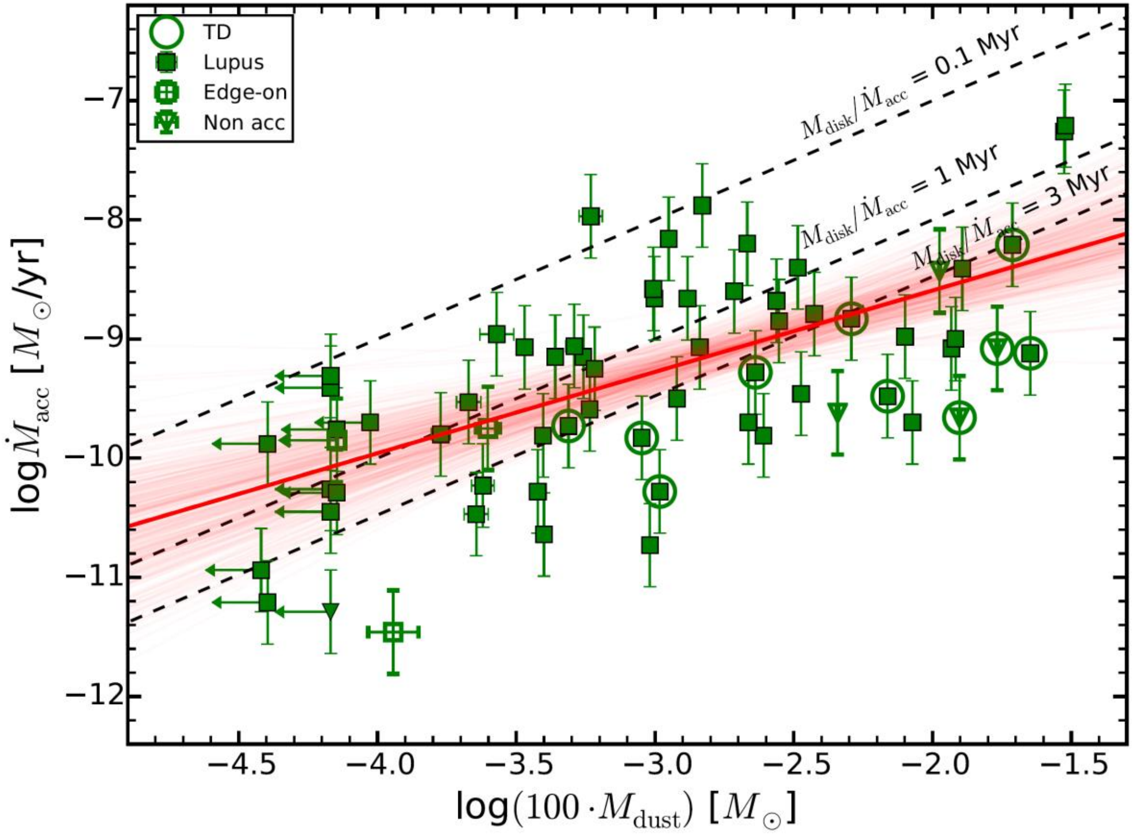
Do they reflect evolution or initial conditions?

Initial conditions	Evolution
Dullemond+ 2006	Pascucci+ 2016
Alexander & Armitage 2006	Pinilla+ 2020
Vorobyov & Basu 2008, 2009	Ercolano+ 2014
Somigliana+ in prep	Somigliana+ in prep

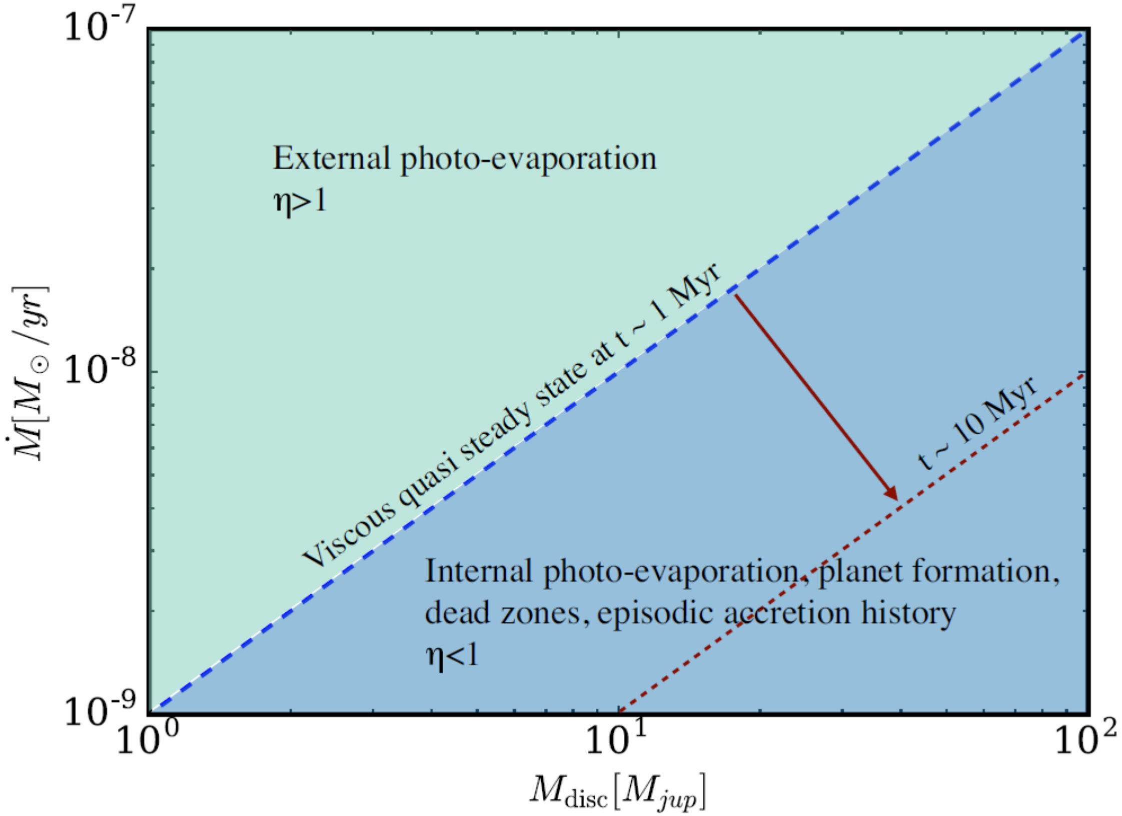
Accretion – disc mass



Accretion rate – disc mass correlation



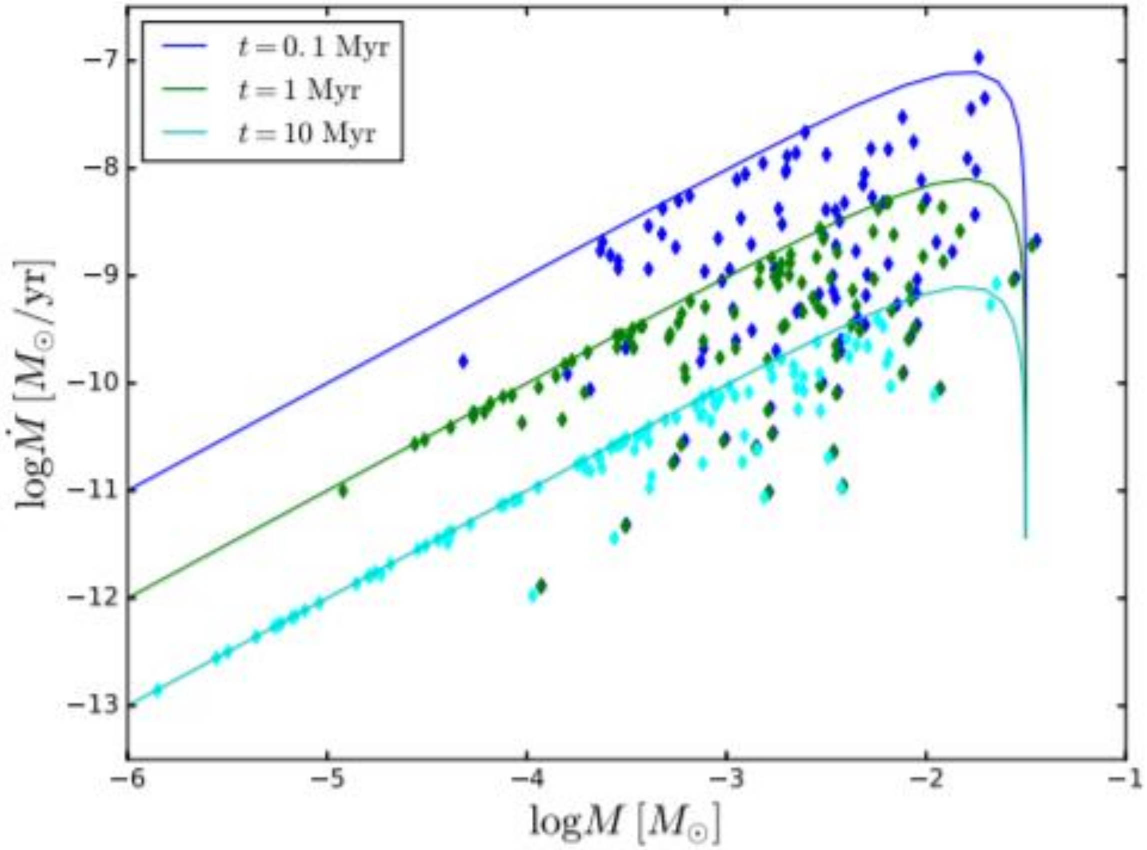
Manara+ 2016



Rosotti+ 2017

Correlation between accretion rate and disc mass is a signature expected from viscosity

Information in the spread

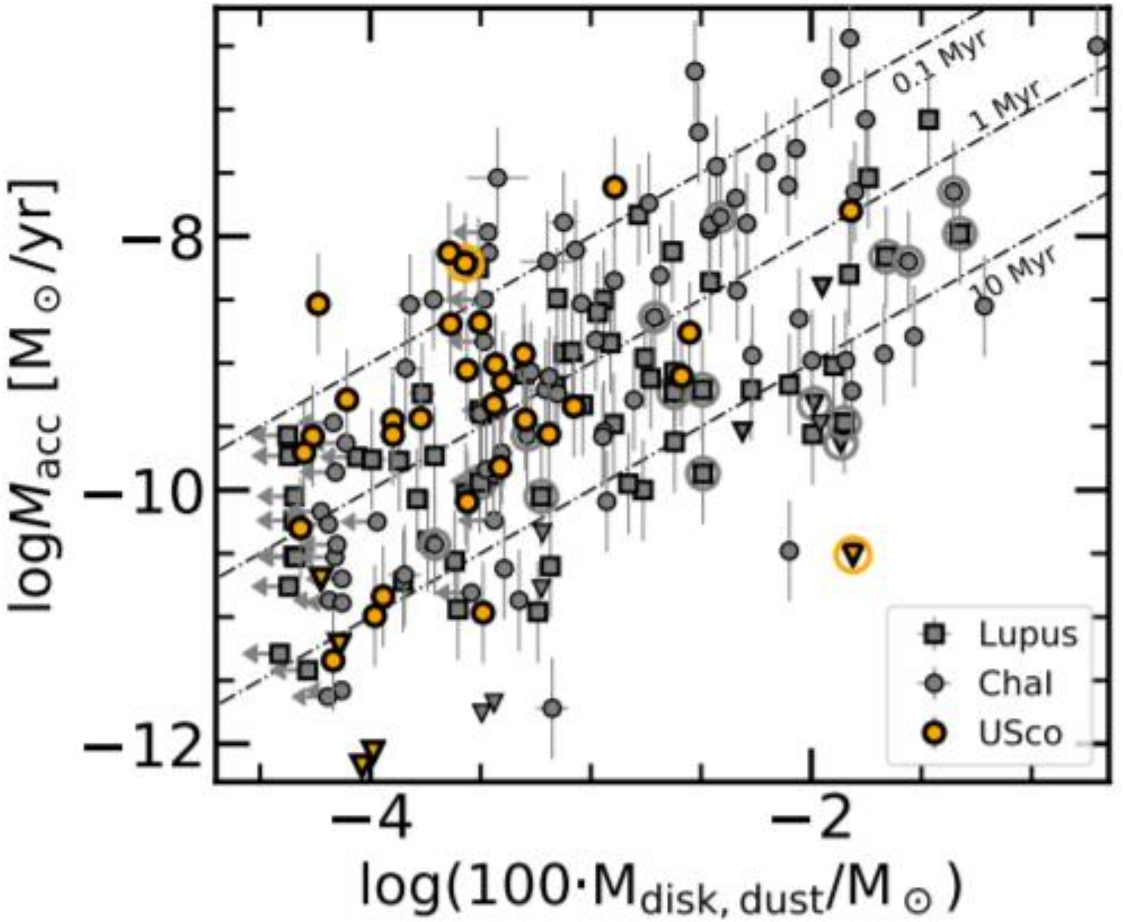


Lodato+ 2017

In the viscous picture spread should reduce with time

Reproducing Lupus requires low viscosity $\alpha \sim 5 \cdot 10^{-4} h_{0.1}^{-2} R_{10}^{3/2}$

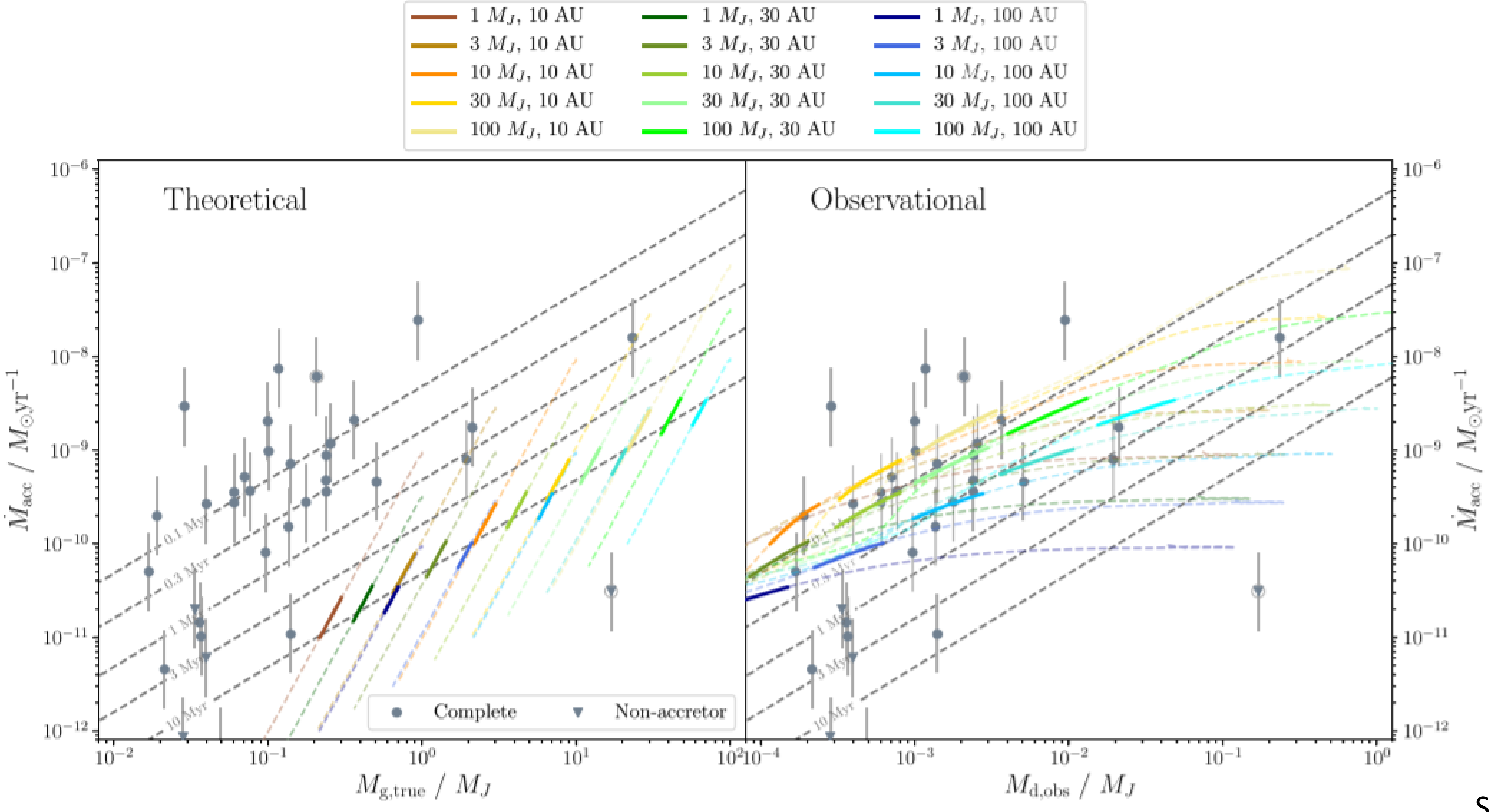
Picture gets complicated – Upper Sco



Manara+ 2020

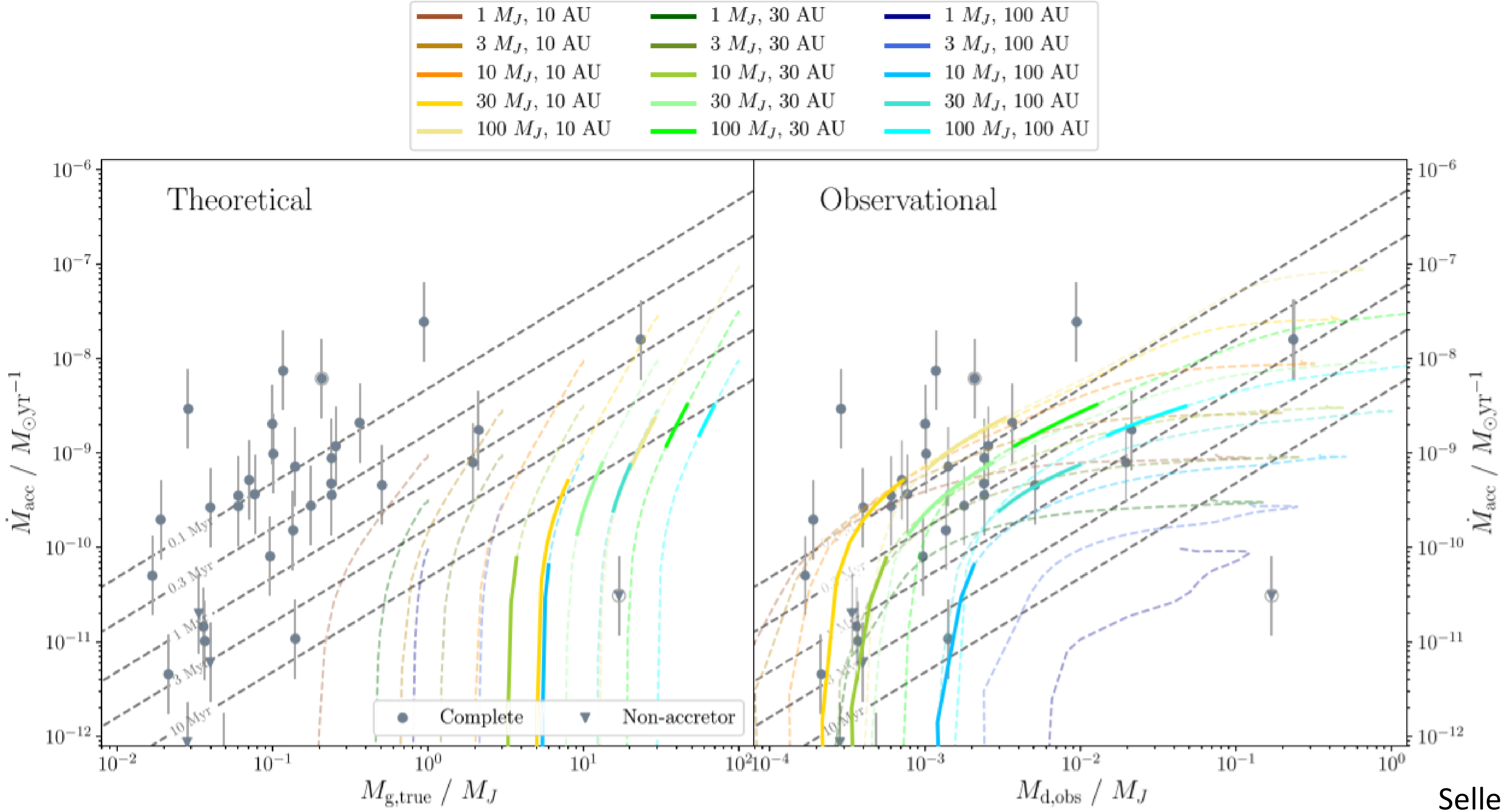
Spread in Upper Sco is comparable to Lupus and ChaI

Viscous scenario "rescued" by dust evolution



Sellek+ 2020b

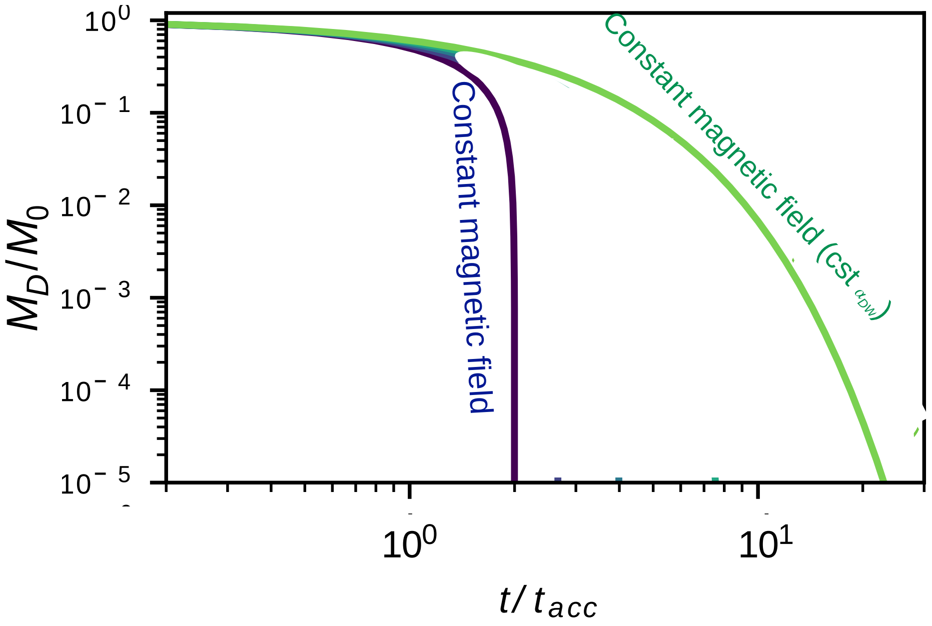
Spread can be improved adding photo-evaporation

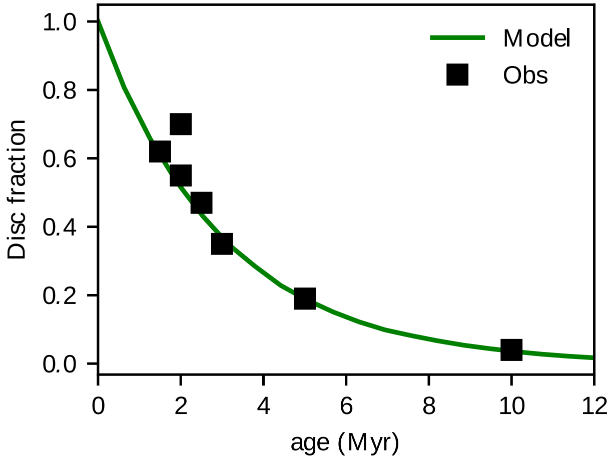


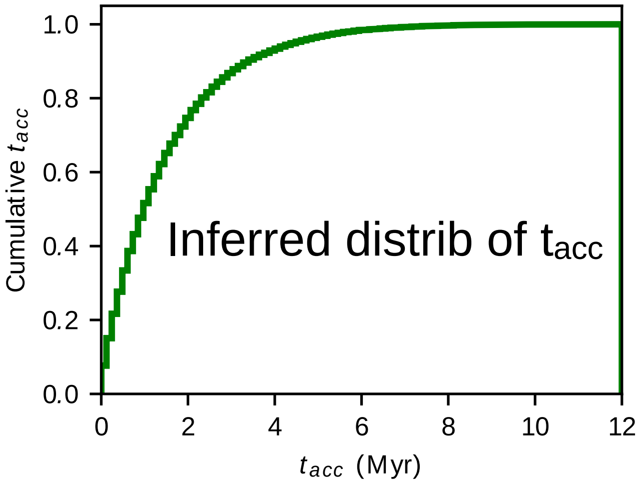
Sellek+ 2020b

Disk dispersal: fitting the distribution of tacc

Constant magnetic field strength leads to fast dispersal after 2t_{acc} !!
=> reconstruct initial distrib of to match disk fraction





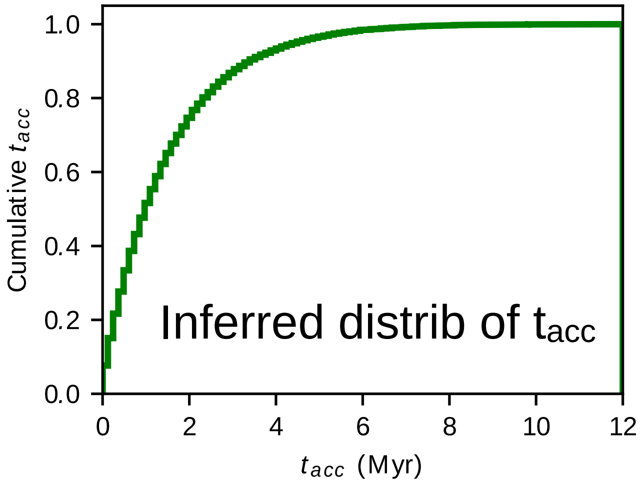


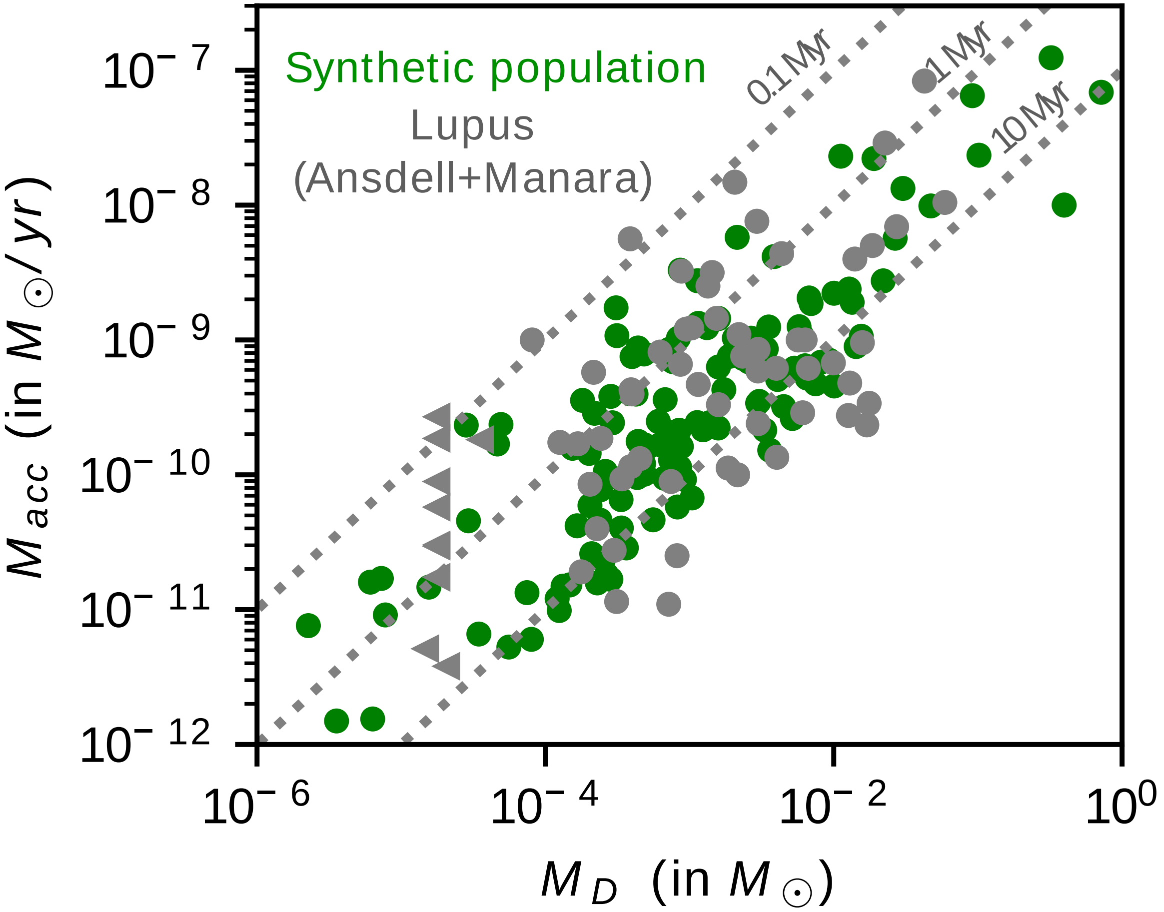
Inferred distrib of t_{acc}

Tabone+ submitted

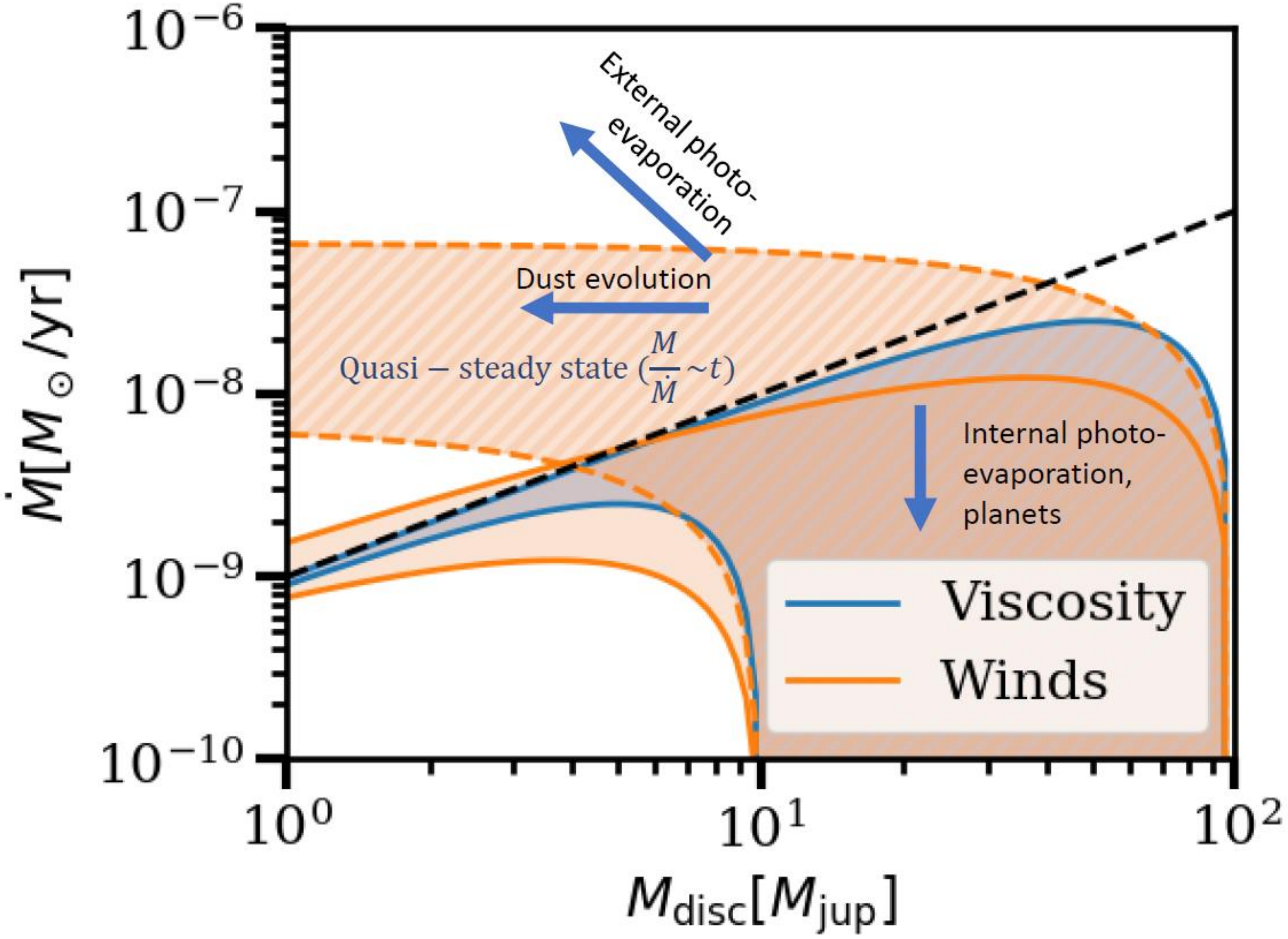
MD-Macc correlation

Disk population approach: tacc inferred from disk fraction
+ assume a distrib in initial disk mass



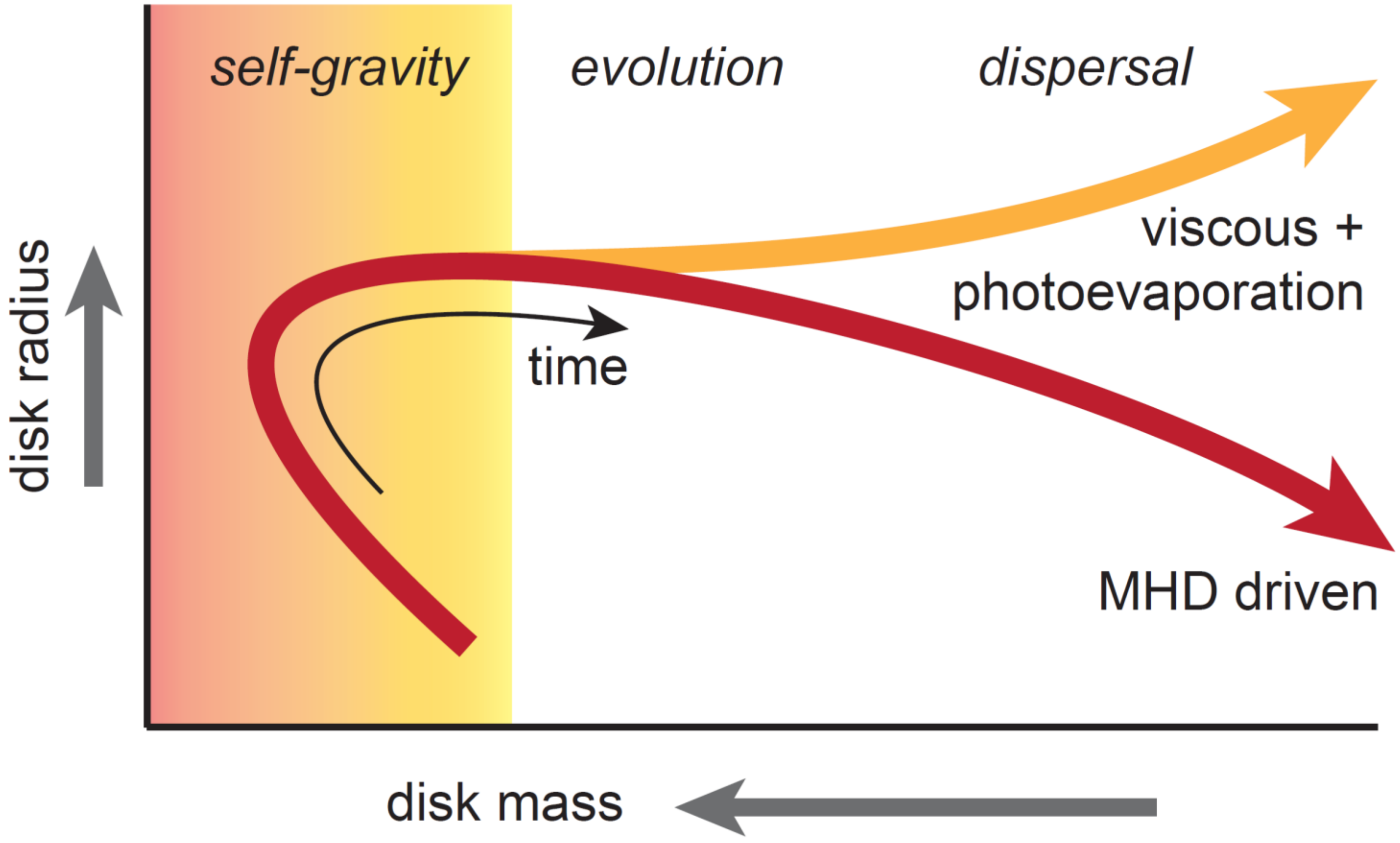


Summary of expectations

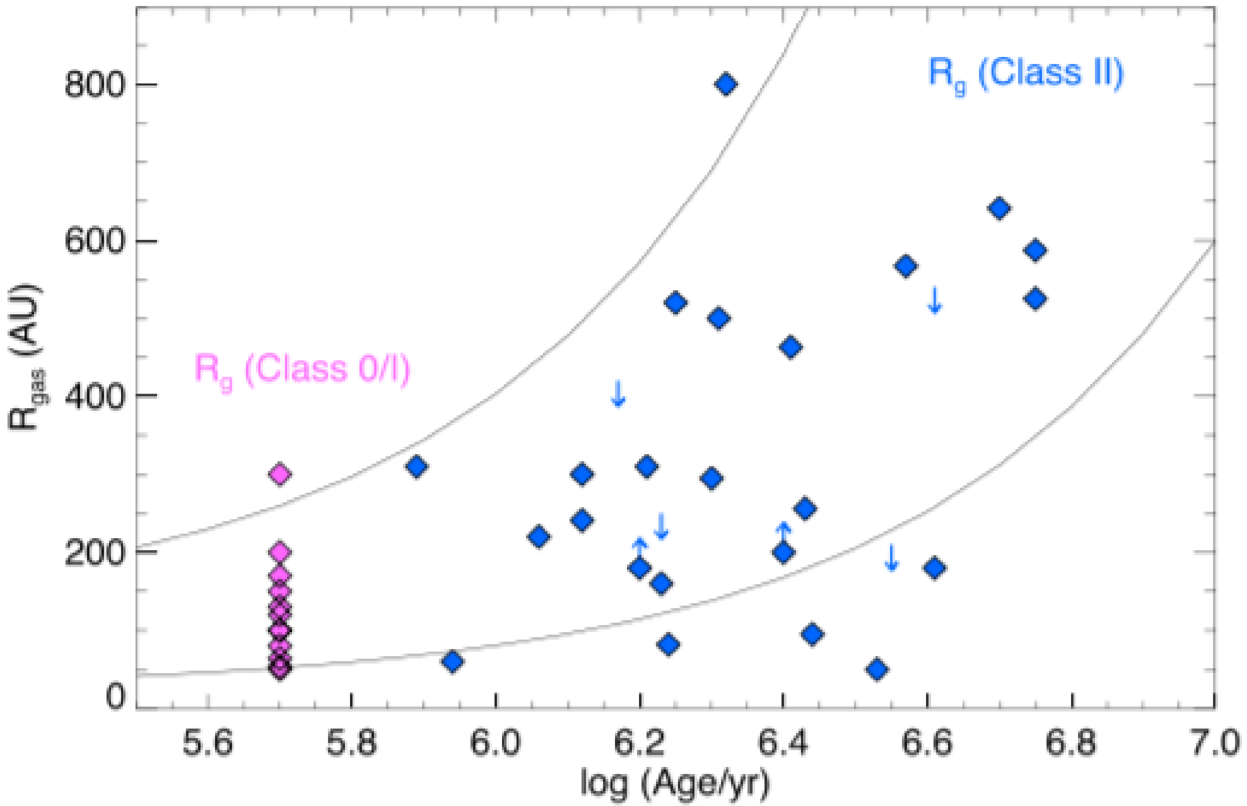


Resolved observations

Radius evolution



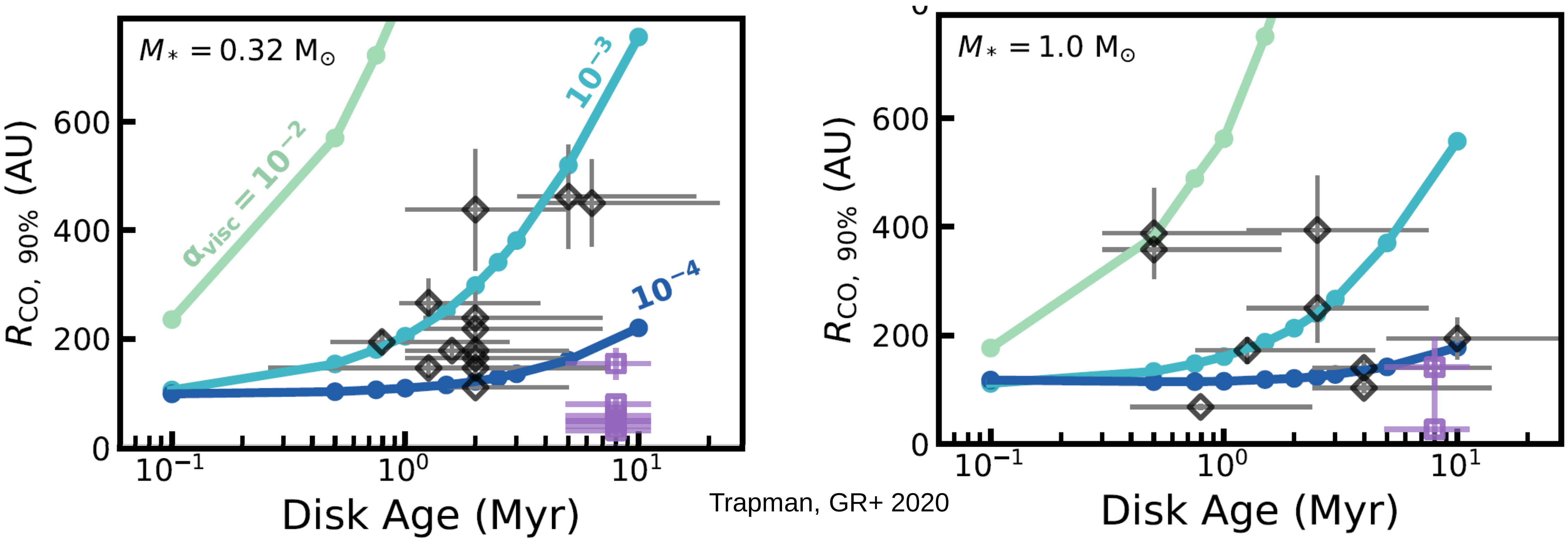
Evidence of viscous spreading?



Najita & Bergin 2018

Tentative evidence, but inhomogeneous sample

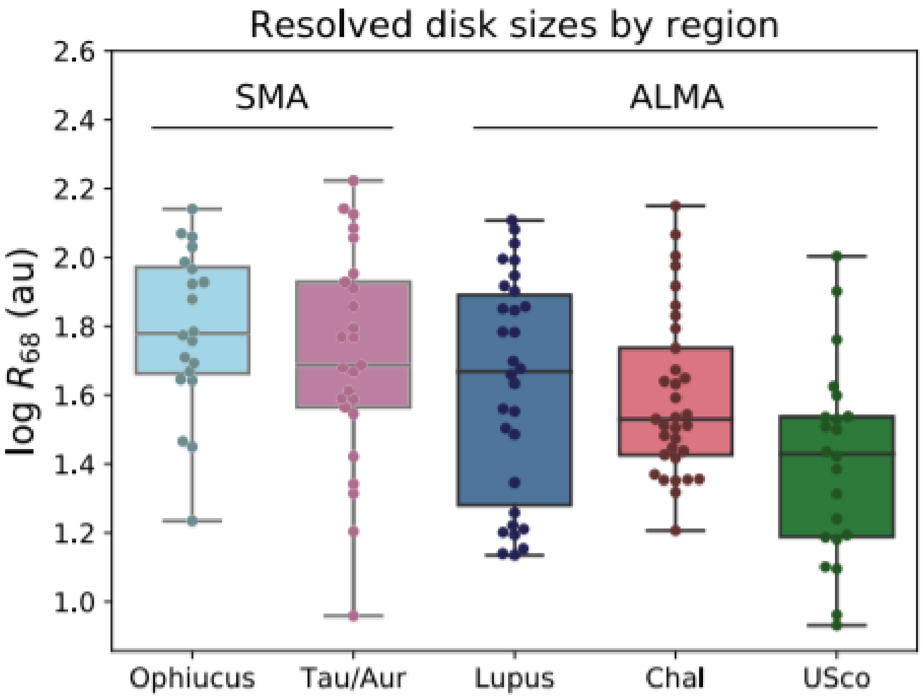
Detailed modelling



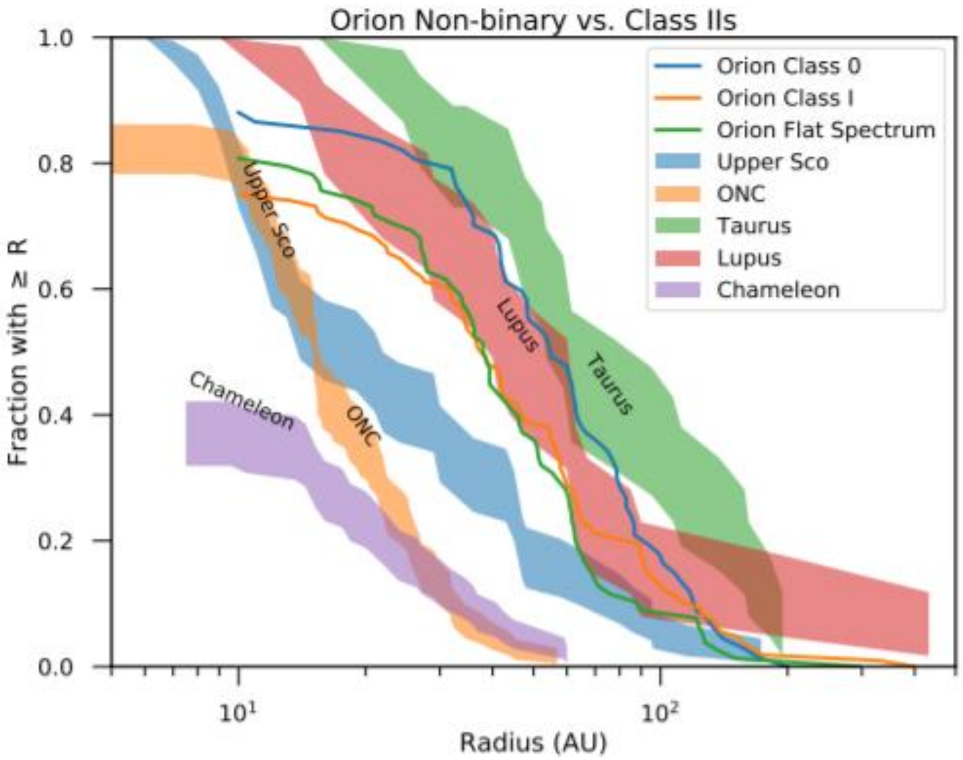
Trapman, GR+ 2020

Excludes discs are highly viscous: observed discs are not large enough
Data too sparse to confirm/reject that disc size increases with time

Dust radii



Hendler+ 2020



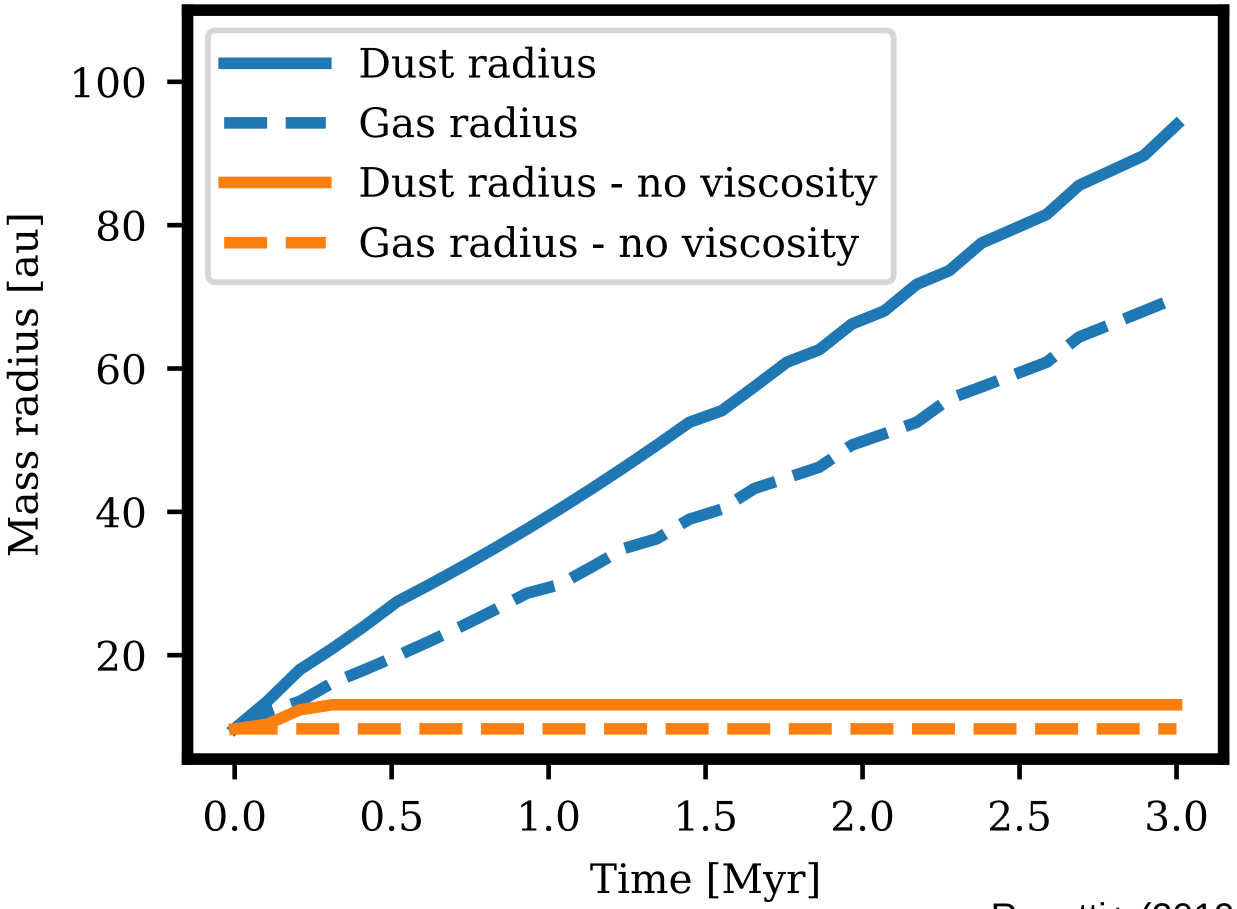
Tobin+ 2020

Class 0/I unclear but otherwise shrinking observed

Theoretical expectations

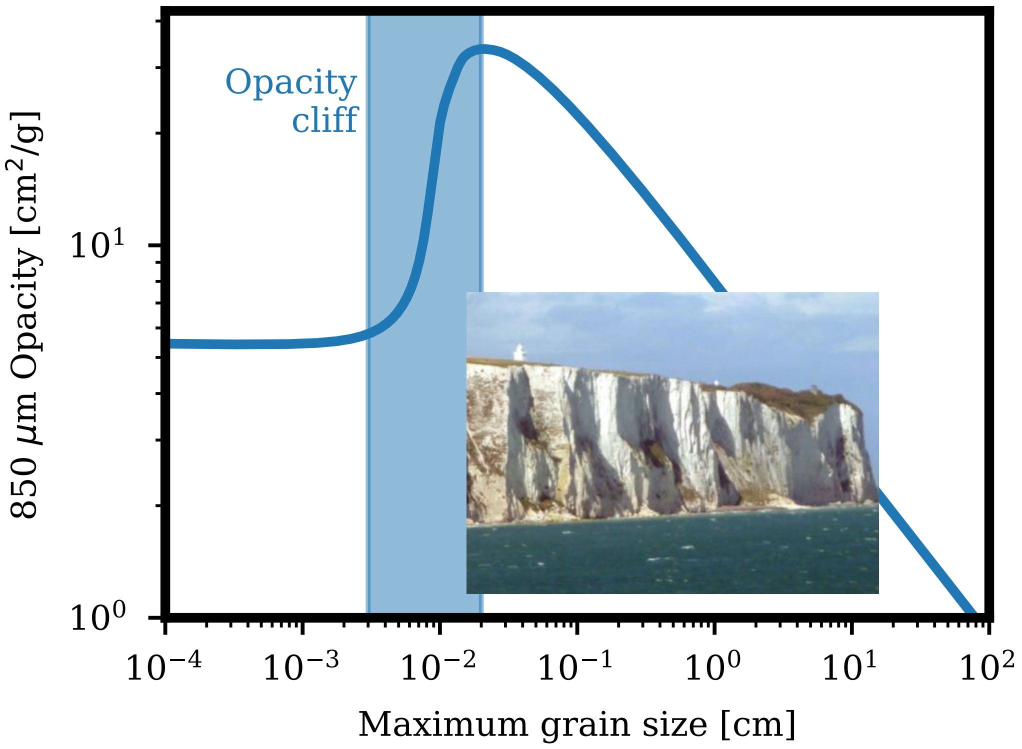
In models of dust growth viscous spreading (if present) “wins” over radial drift

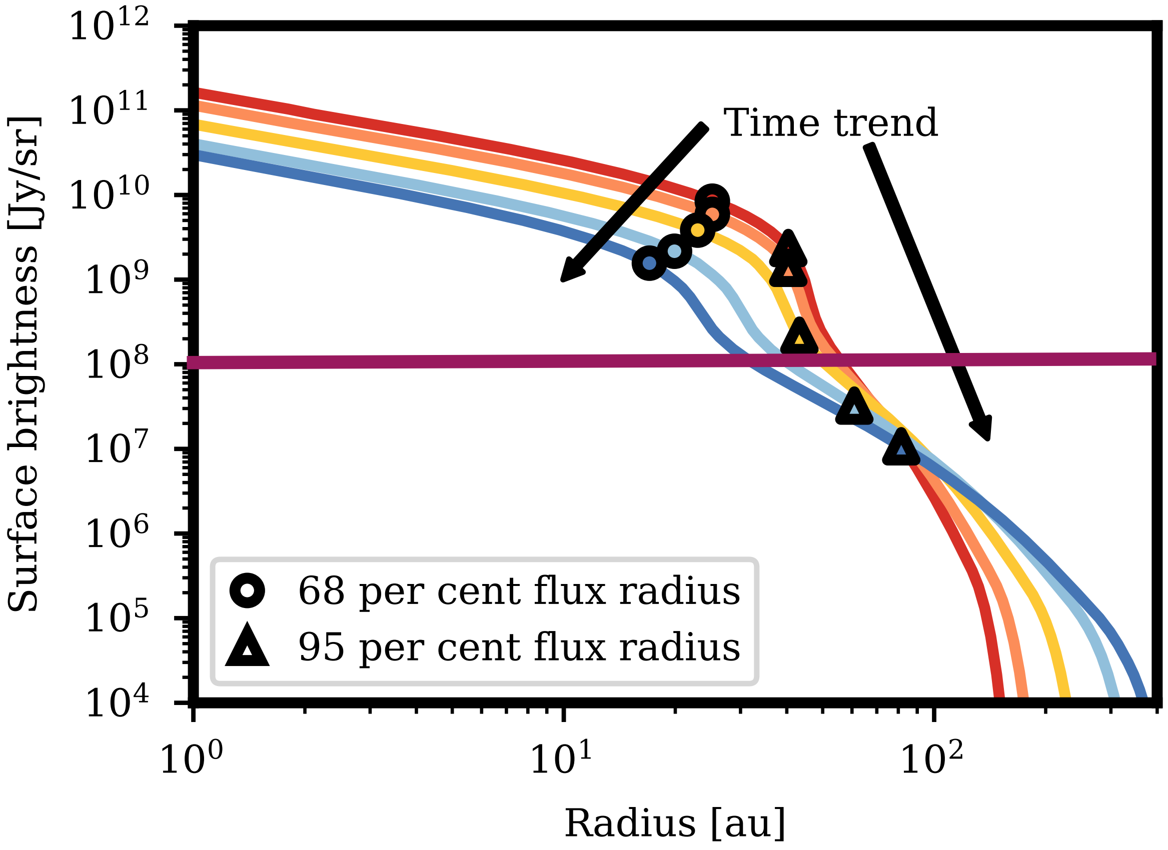
It is not entirely correct to say “dust discs are small because of radial drift”



Rosotti+ (2019a)

…but they *do* look small!



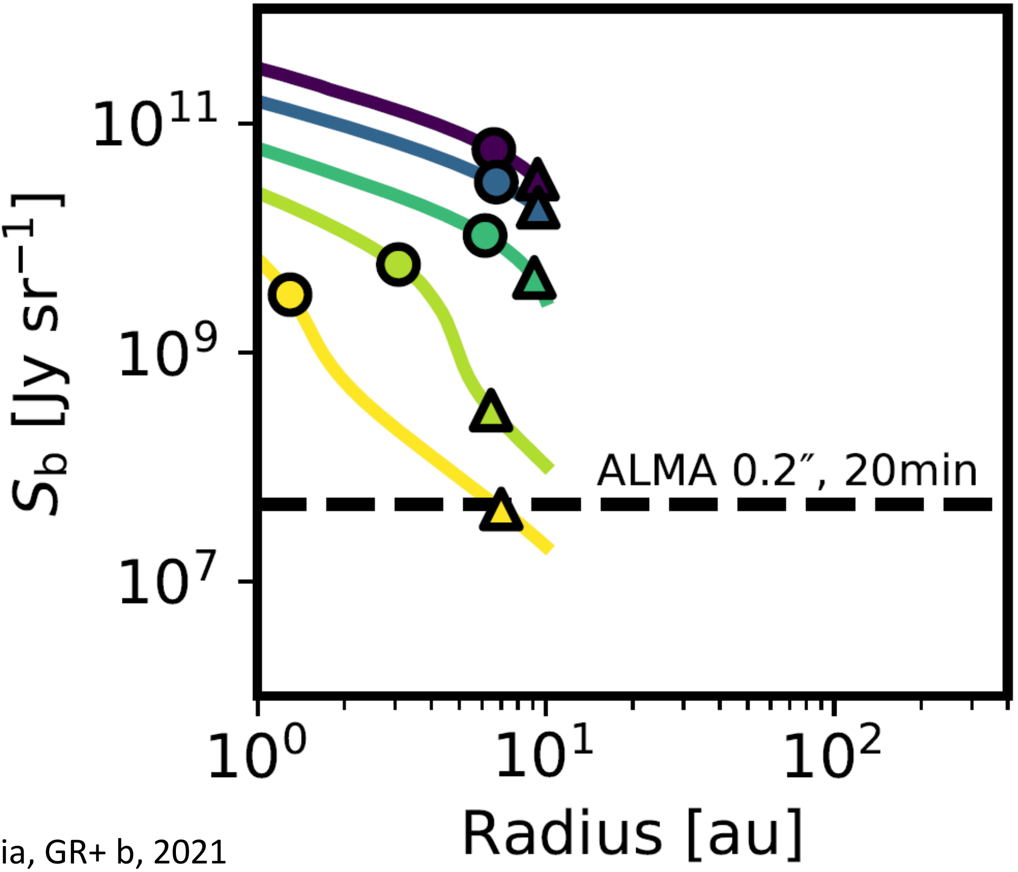


Sensitivity of
typical ALMA
survey

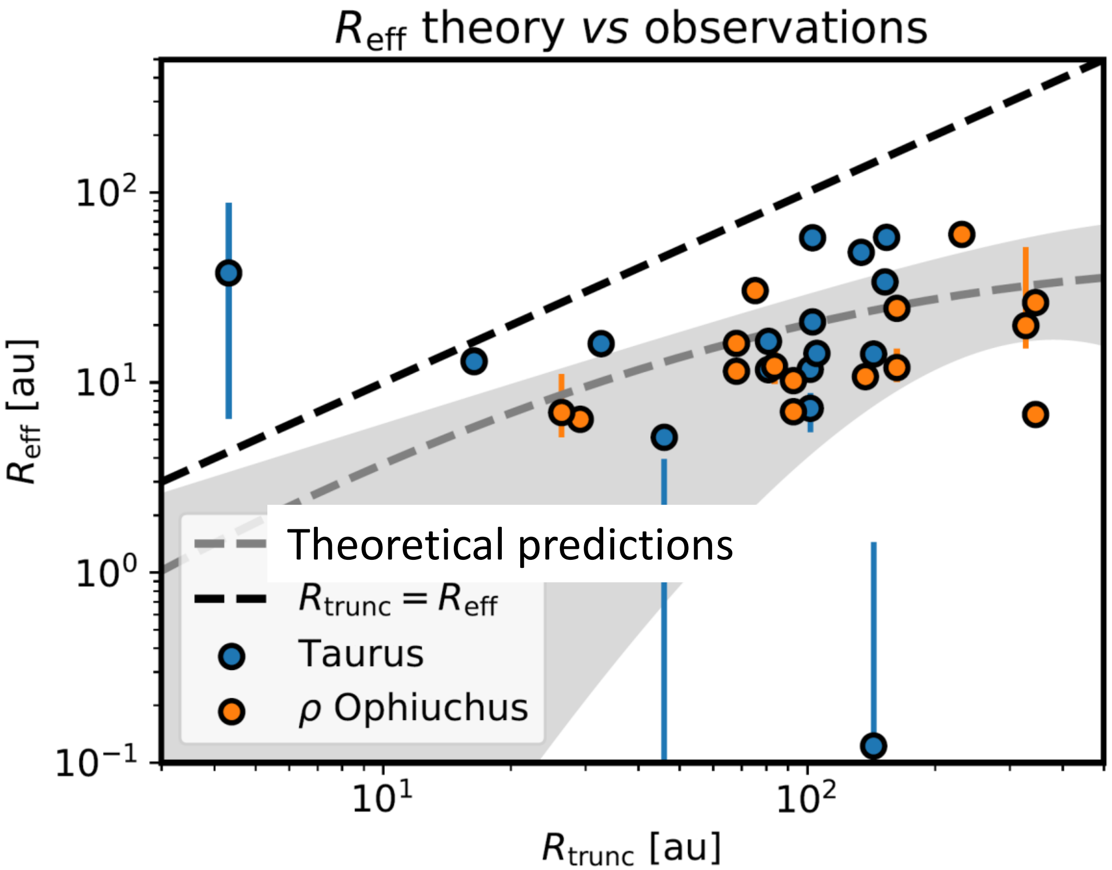
Rosotti+ (2019a)

Radial drift makes the grain small
Small grains have little opacity – the disc *looks* smaller

Parenthesis: dust disc radii in binaries do *not* trace the truncation radius

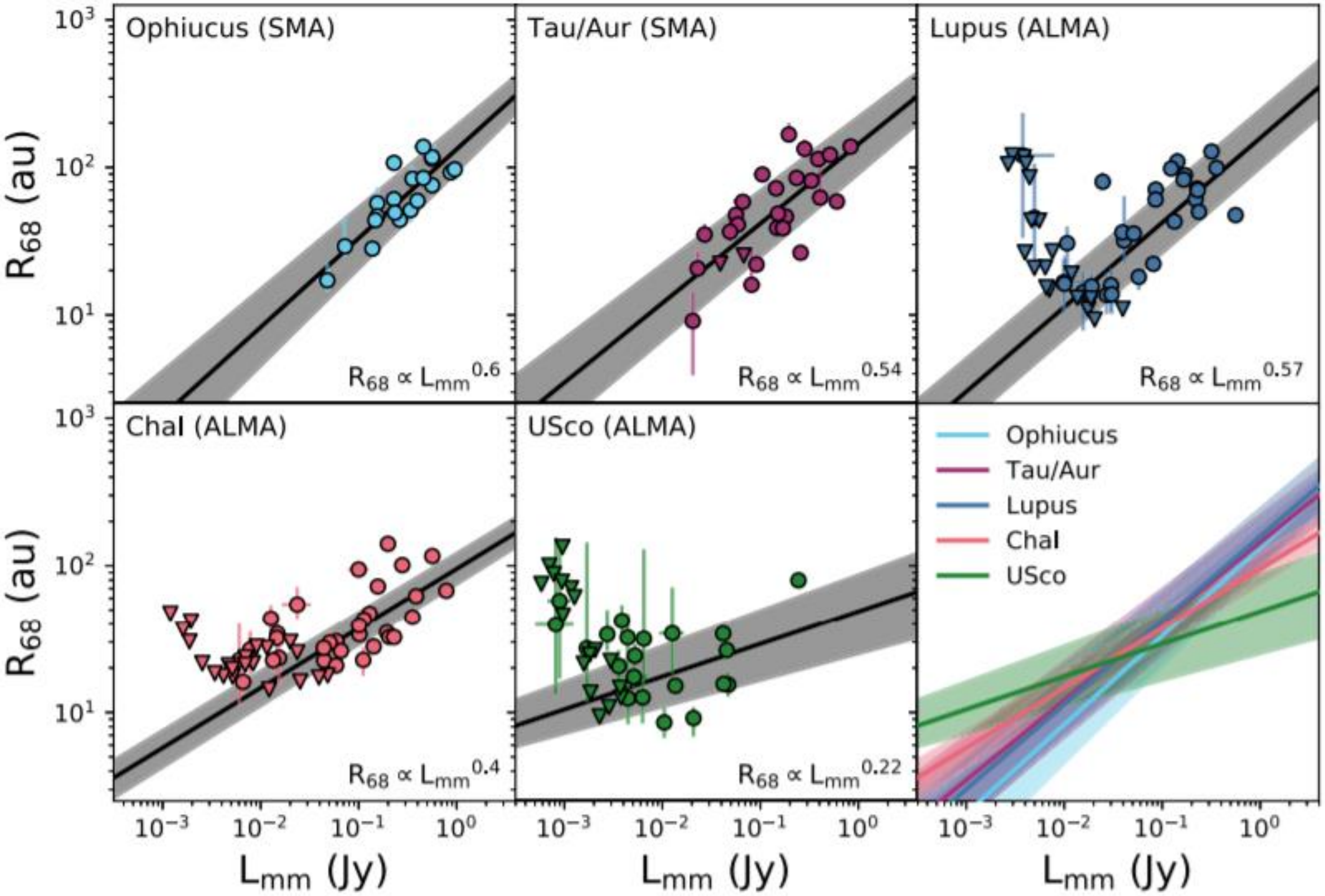


Zagaria, GR+ b, 2021
See also GR & Clarke 2018



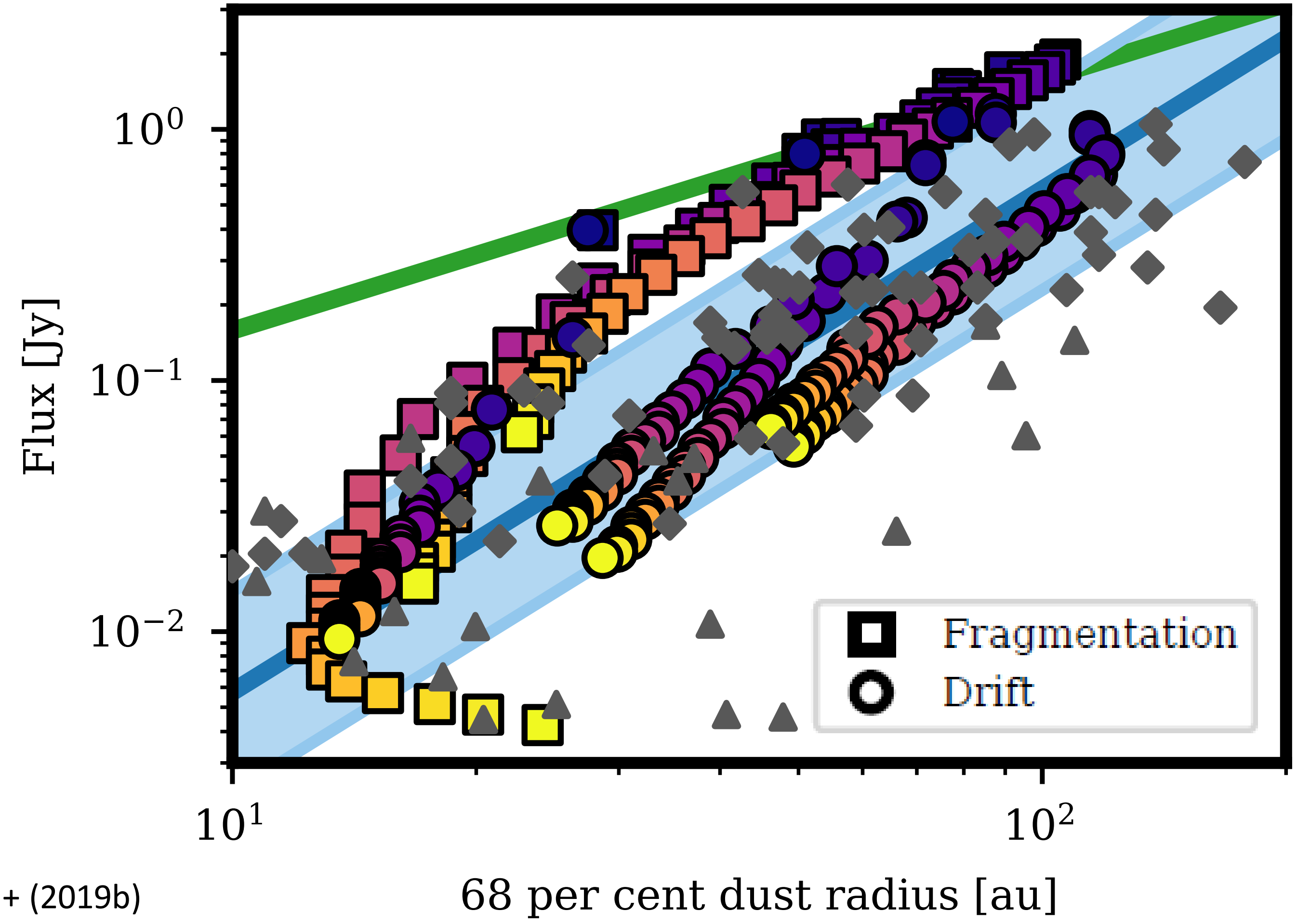
No need to require highly eccentric orbits (Manara+ 2019)

Flux radius correlation



Hendler+ 2020
See also Tripathi+ 2017, Andrews+ 2018

Flux-radius relation

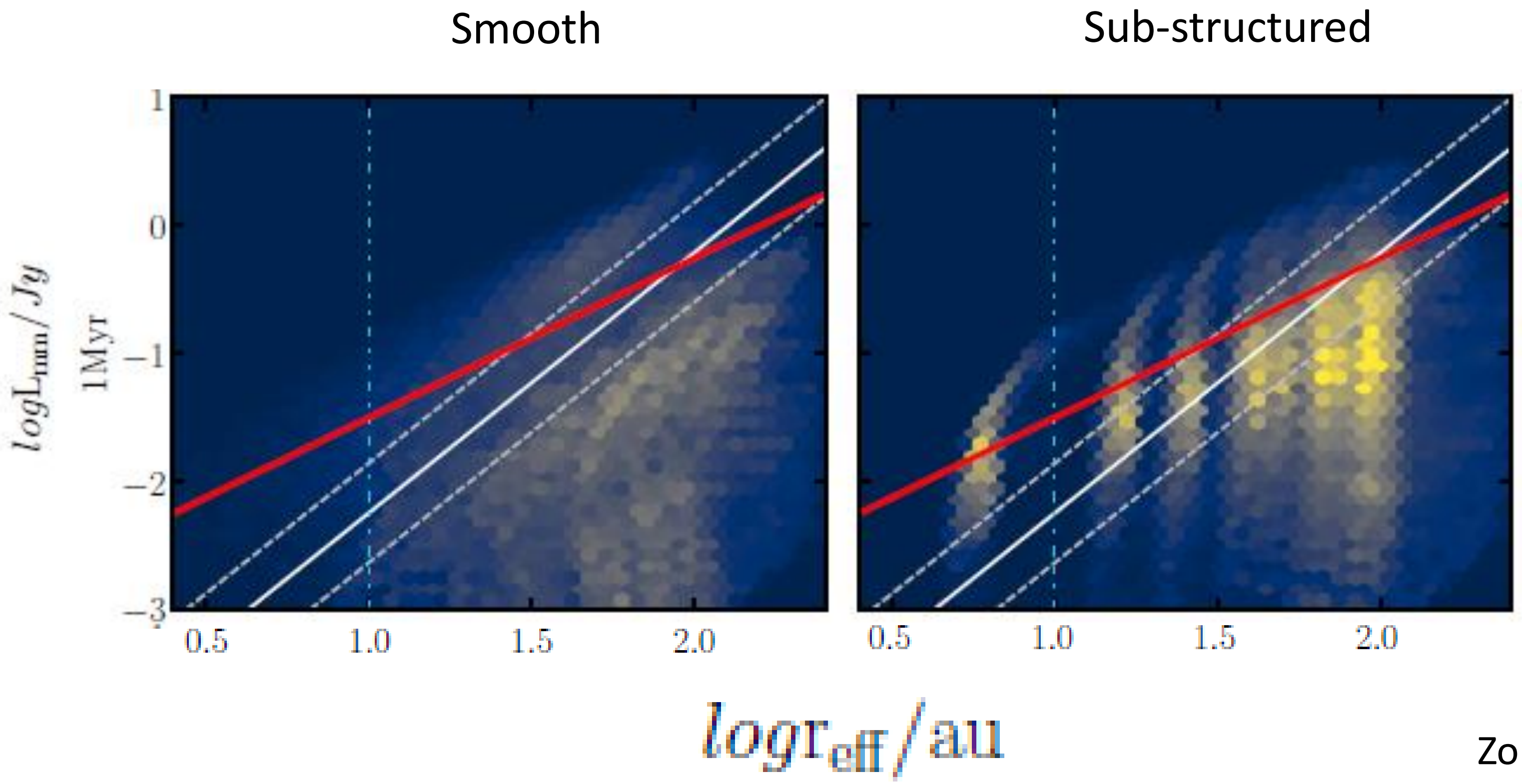


Rosotti+ (2019b)

Data from Tripathi (2017), Andrews (2018)

Can be explained by smooth models of dust radial drift

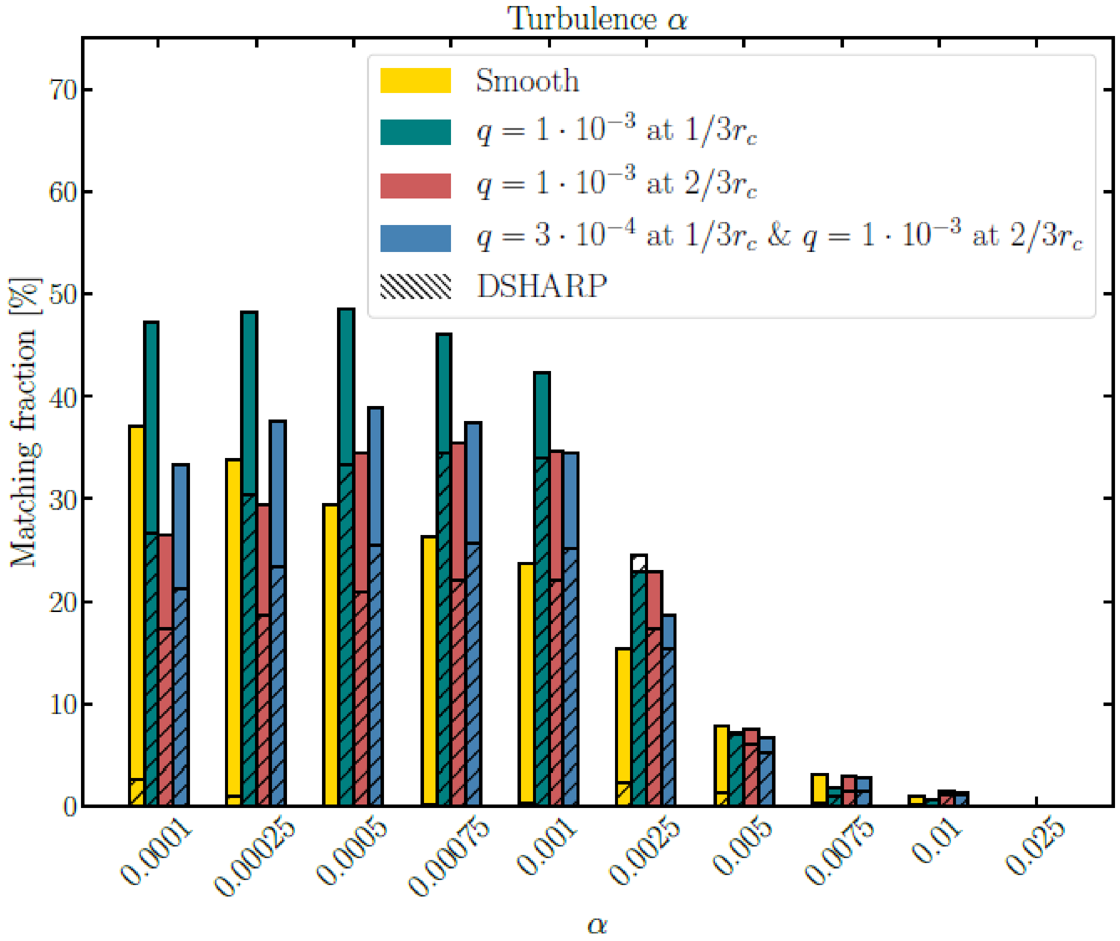
Flux-radius relation



Zormpas+, submitted

But easier to explain with models including sub-structure
Slightly different slope

Relation requires low viscosity



Zormpas+, submitted

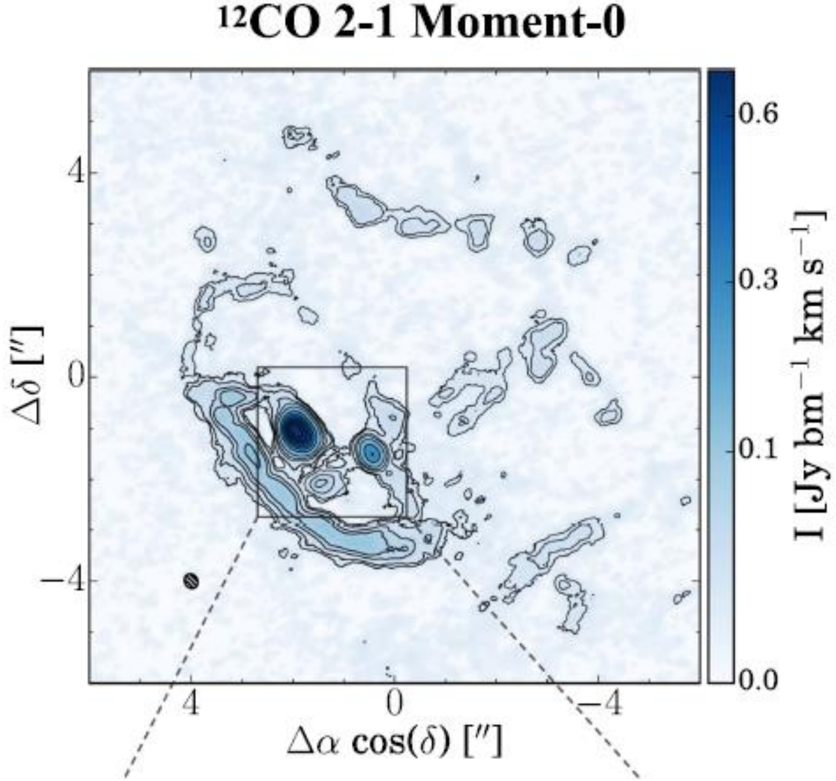
Both for models with/without sub-structures

Effects of the environment

Two mechanisms

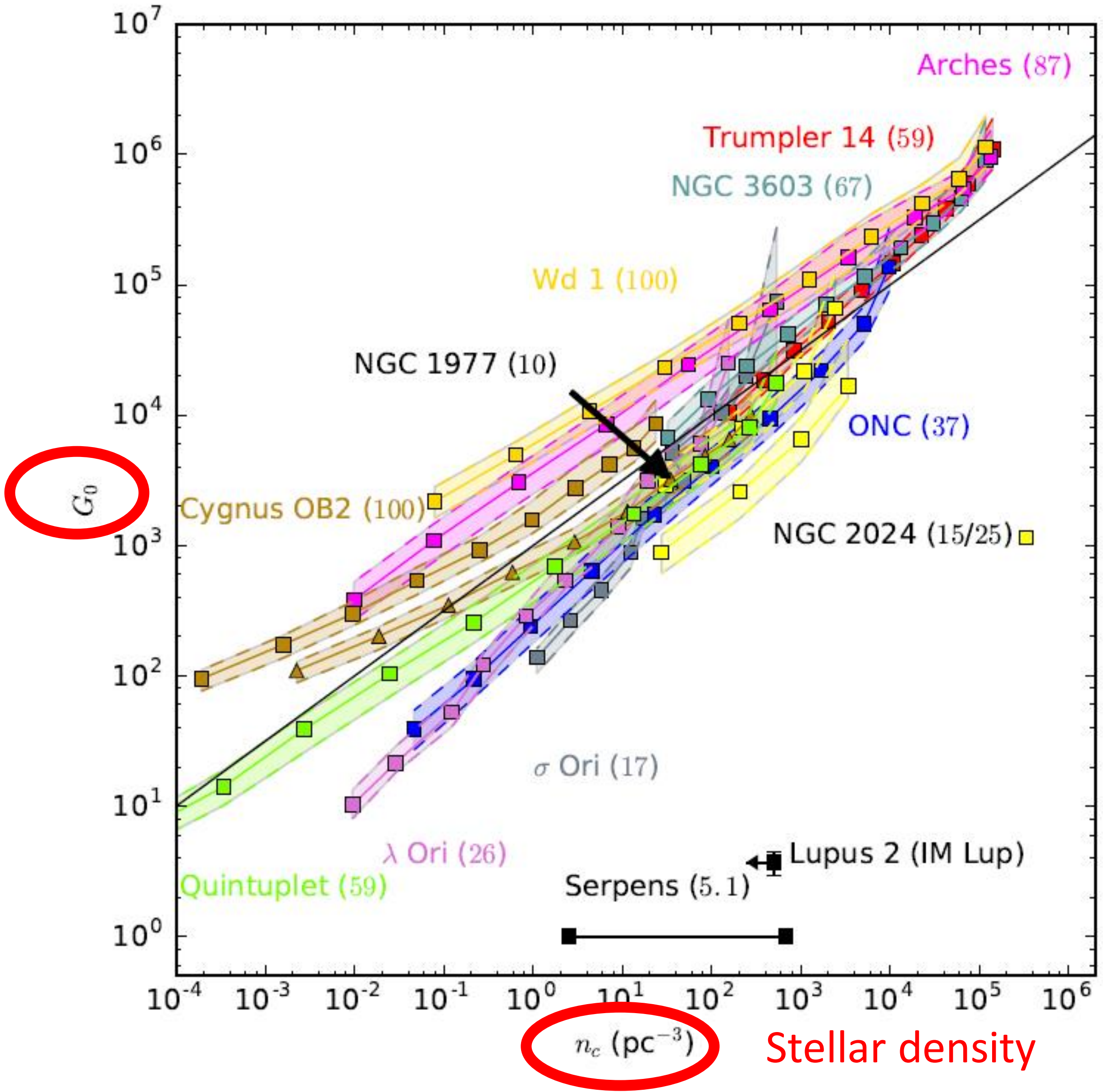
External photo-evaporation

Encounters



RW Aur, Rodriguez+ 2018

Encounters or irradiation?

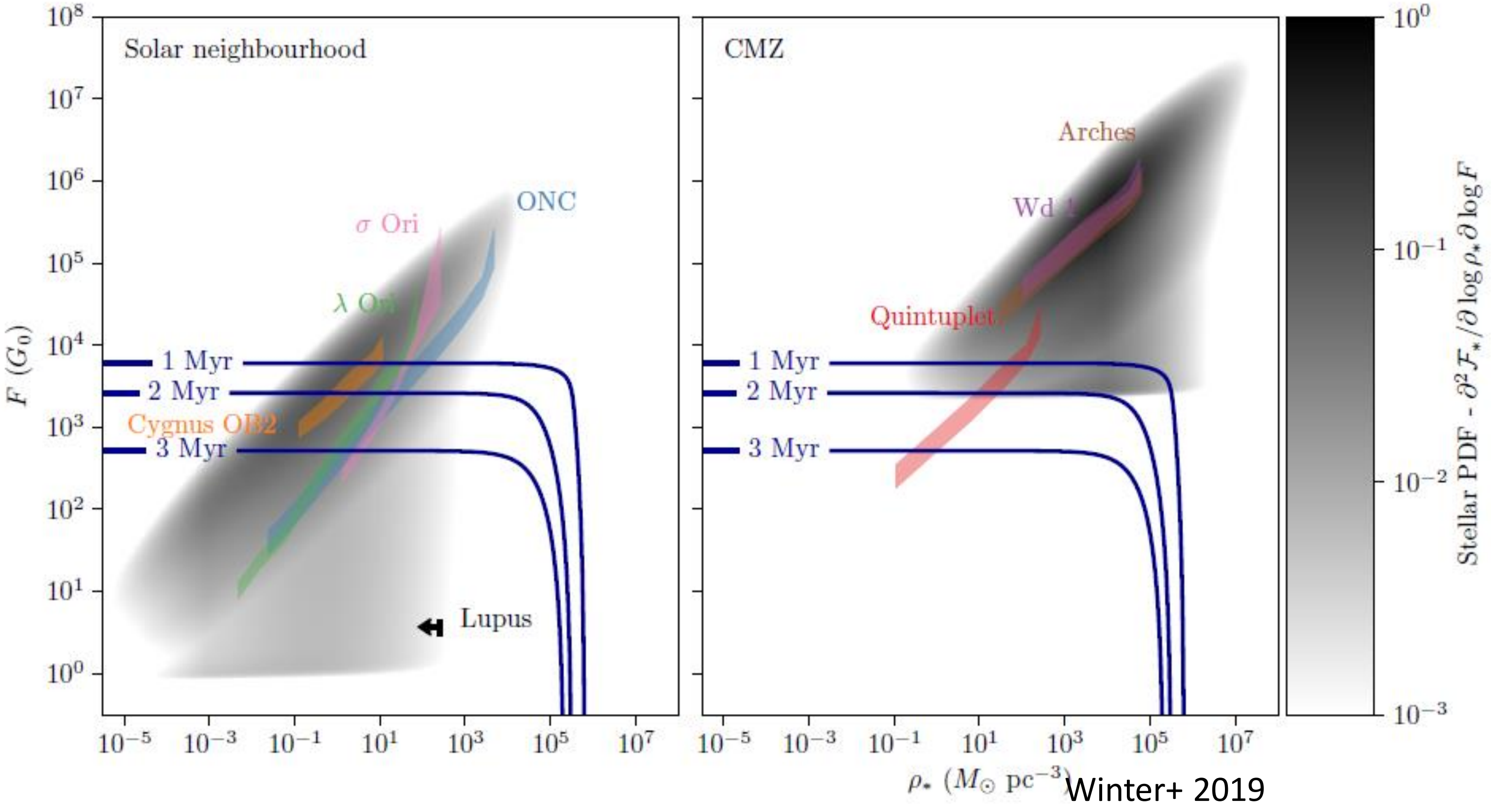


Level of irradiation

Stellar density

Winter, Clarke, GR+ 2018
Using external photo-evaporation models from Facchini+ 2016 and Haworth+ 2018

Where did the average star form?



Winter+ 2019

50% (in the solar neighbourhood) in regions affected by external photo-evaporation

Thus:

a) The average disc is NOT from Taurus or Lupus
b) Reinforces idea that planet formation is fast

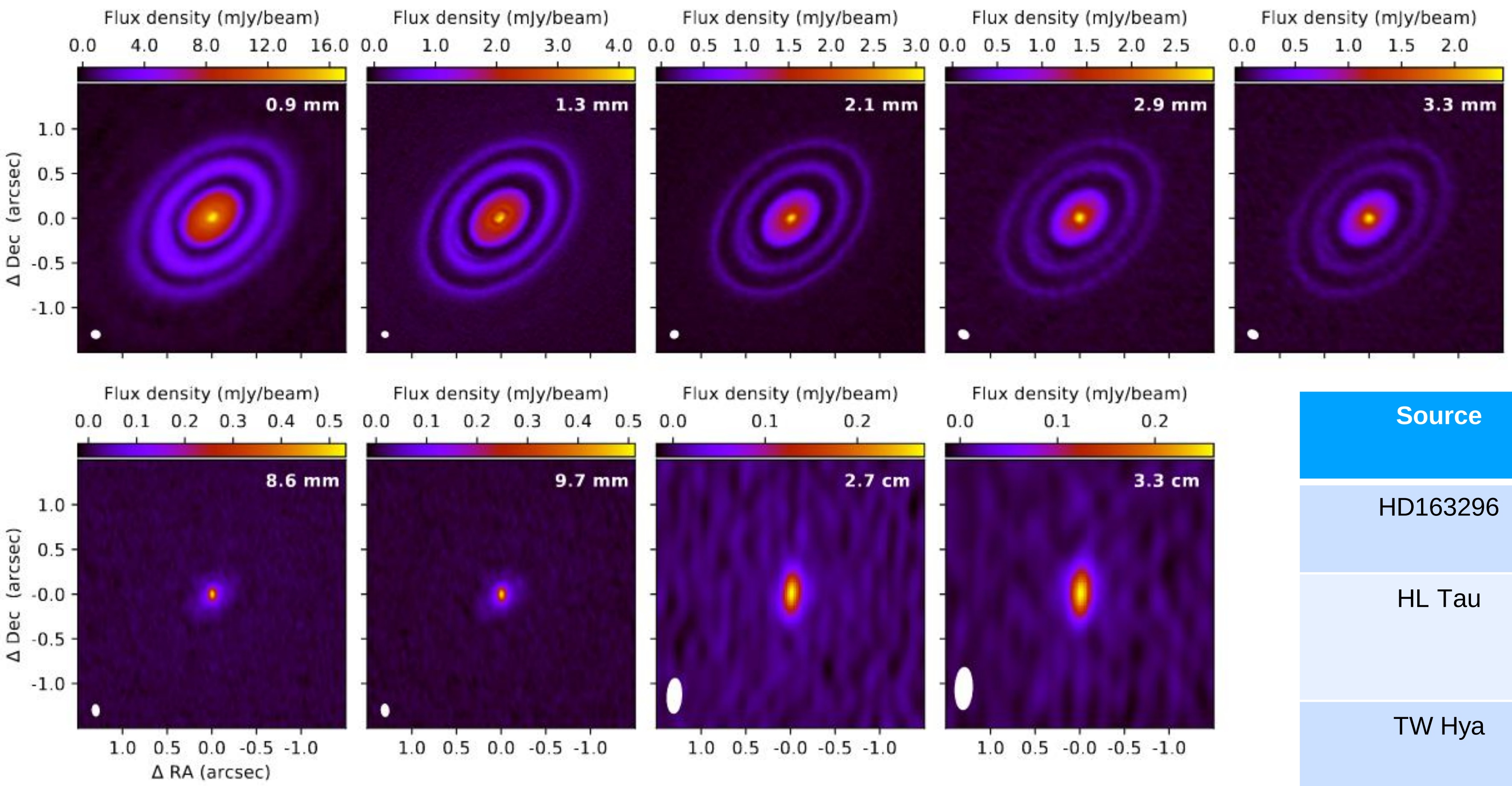
Open questions 1

$$M_{\mathrm{dust}} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\mathrm{dust}})}$$

Is this a good way to measure the disc (solid) mass?

- Unknown temperature (most likely limited effect)
- Unknown opacity
- Potentially optically thick (and potentially at high albedo, Zhu+ 2019)

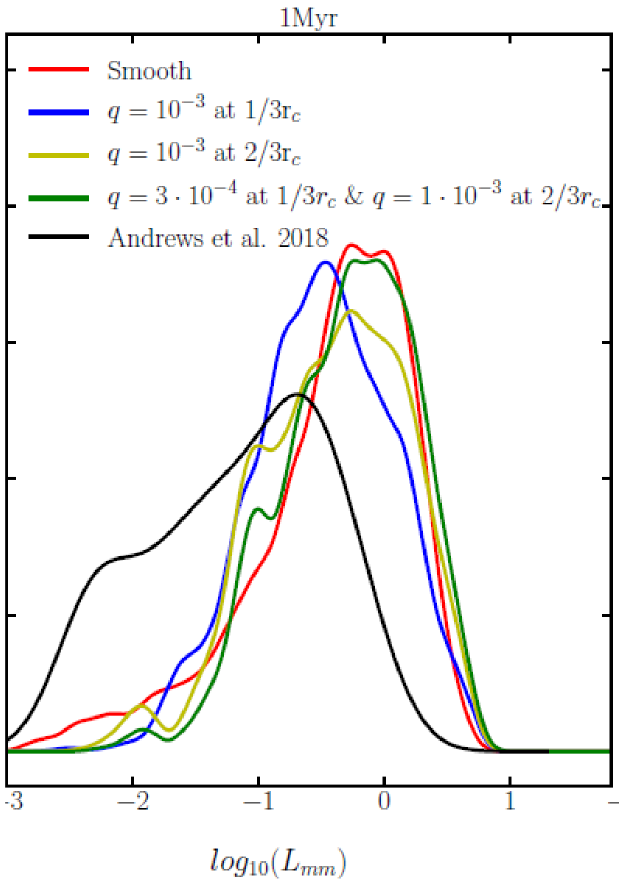
Spatially resolved multi-wavelength studies

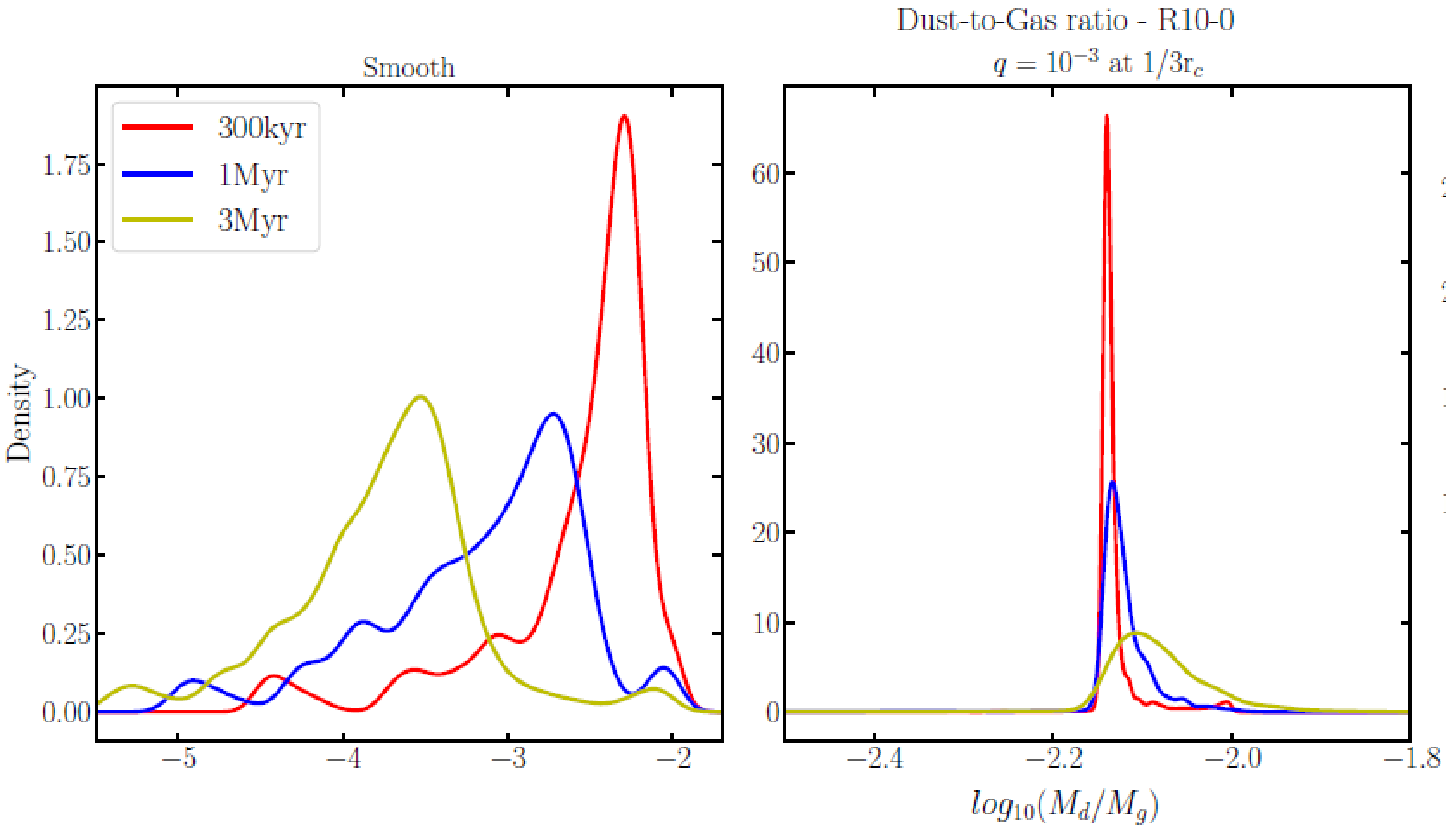


Source	"Correction" factor	Reference
HD163296	~1.7	Guidi et al, submitted
HL Tau	~3	Carrasco-Gonzalez et al, 2019
TW Hya	~5	Macias et al 2021

HD163296, Guidi+, submitted

Modelling





Zormpas+, submitted

Models with/without substructure have similar fluxes, but different dust masses

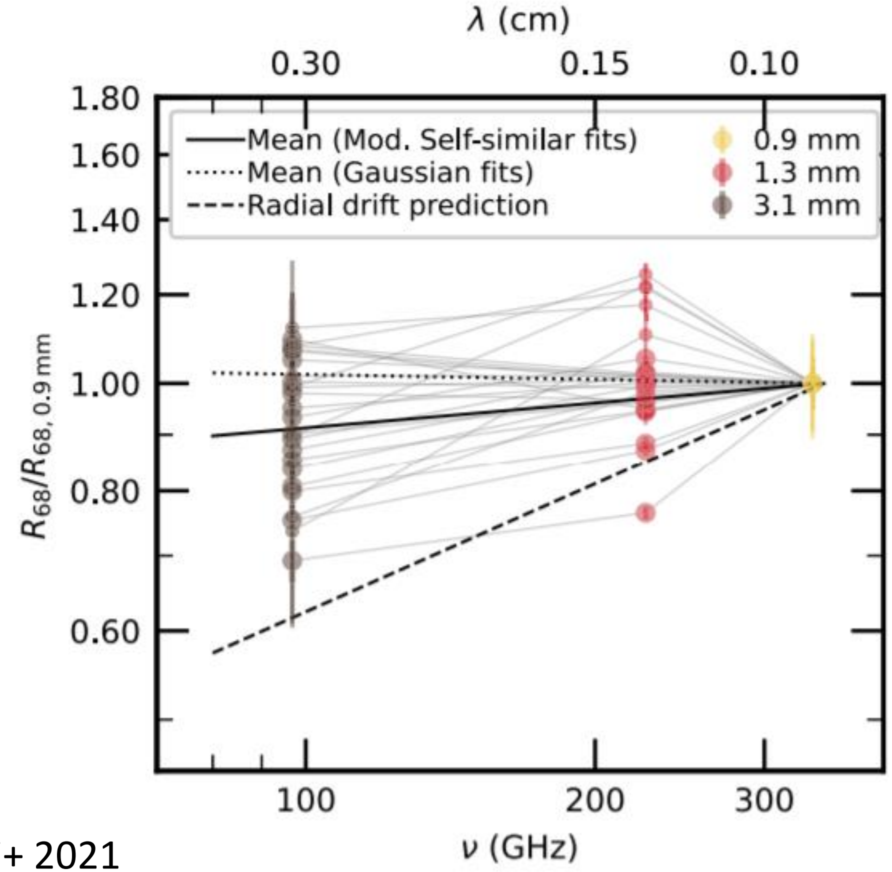
Open questions 2

What is the prevalence of disc substructure? Are *all* discs sub-structured? (see e.g. Jennings talk)

Indirect evidence:

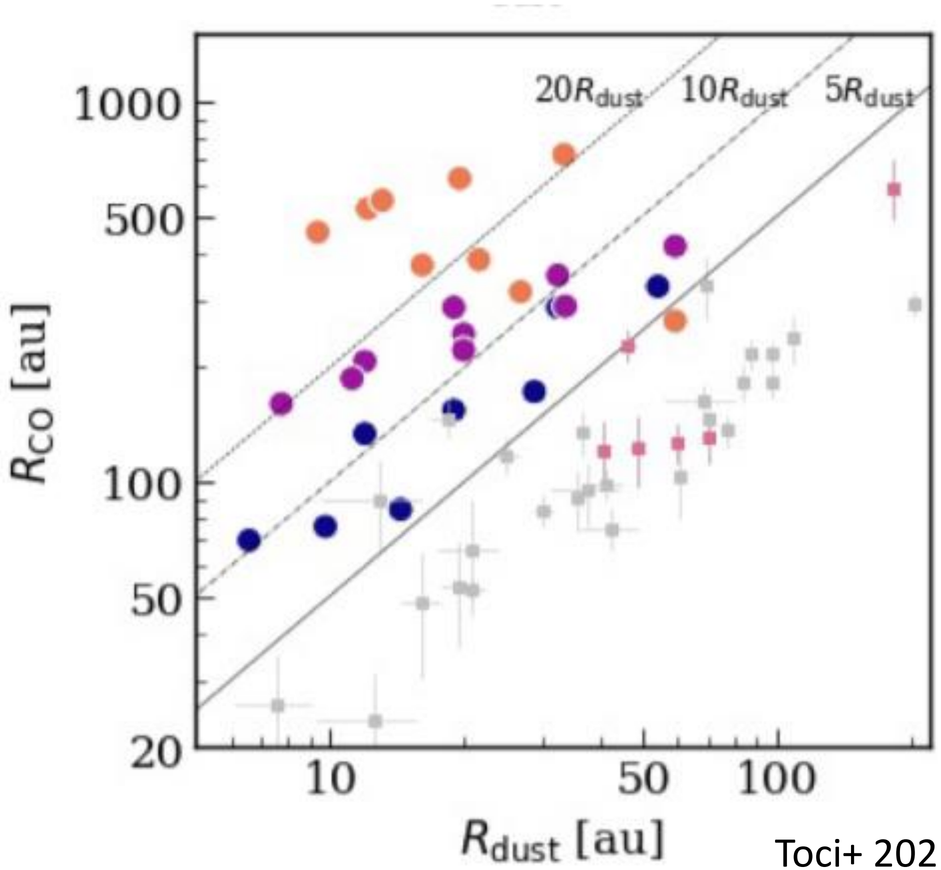
- Flux-radius correlation (Zormpas+ 2021)
- Rdust/Rgas (Toci+ 2021)
- Dust sizes at different wavelengths (Tazzari+ 2021)

Indirect evidence



Tazzari+ 2021

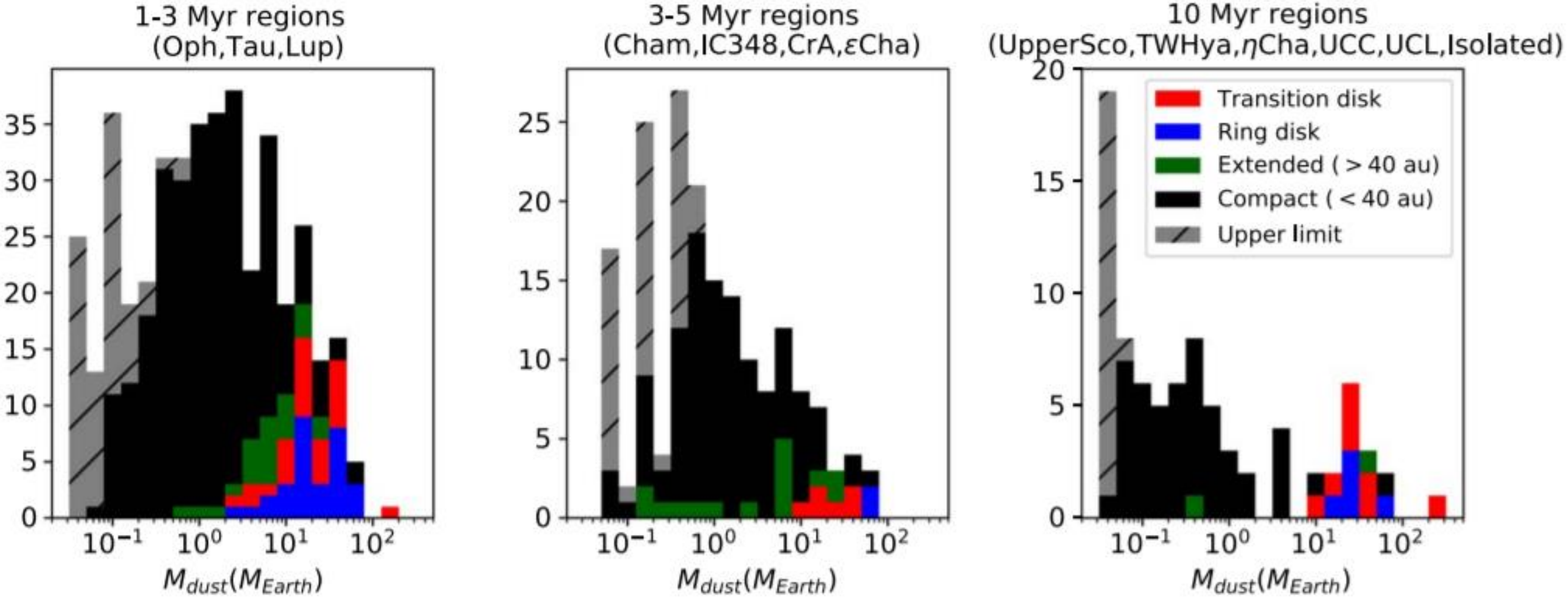
Little variation of disc size with wavelength



Toci+ 2021

Dust discs are not much smaller than gas discs

Counter-argument



van der Marel & Mulders 2021

Two evolutionary paths for structured/non-structured discs?

Take home messages

- Massive improvements in our knowledge of the disc demographics
- Viscous framework still working, but progressively challenged
- Early evidence that MHD wind framework is a viable alternative
- Interplay of dust evolution & sub-structure non-trivial